Integrating Human Factors into Chemical Process Quantitative Risk Analysis

vorgelegt von

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To my mother,
"Mum, you build my foundation that grew to be a bridge to cross any river, even the most turbulent"

To my late father Mr. Paul Kariuki,

"Daddy, your spirits give me strength to carry on, every single day."

We now have unshakable conviction that accident causes are man-made and that a manmade problem can be solved by men and women. ~W.H. Cameron

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This work was completed while working at the department of Plant and Safety Technology at the Technical University of Berlin. During this time I met a lot of people who made contributions that have impacted positively in my life. For this reason I say thank you!

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ABSTRACT

Inclusion of human factors in the chemical process quantitative risk analysis (CPQRA) is done by use of human reliability analysis (HRA) techniques. Therefore, to avoid under or overestimation of the actual risk, human error probability (HEP) estimation must be reasonably accurate.

This work was founded on the premise that most HEPs used in CPQRA are plagued with uncertainty and therefore do not represent the actual conditions of the system or plant being analysed. However, it is critical that the potential human causes for major accidents be exhaustively identified and quantified for a complete QRA. There is need to introduce a systematic method to analyse the underlying human factors, which cause errors that lead to accidents. To achieve this, first a qualitative method to assess human factors was developed. It formed basis of introducing the aspects of human factors into quantitative risk analysis. An extended framework to capture human and organisation factors that influence the operator performance in order to identify the actual error producing conditions that lead to basic events has also been described in this work. These factors are used to adjust the existing HEPs or the ones that are estimated by experts.

The work was accomplished in the following steps:

i) Development of a qualitative human factors assessment tool. The tool covers the whole human factors spectrum and could be used for auditing HF maturity level for a given plant.
ii) Development of a framework to identify human error events and to analyse human and organisational factors behind these error events. This information is critical in establishing the influence that impacts indirectly yet powerfully the probability of an accident.
iii) Quantification of the human and organisational factors for quantitative risk analysis (QRA). An important part is weighting of HF that was done by use of a questionnaire sent to industrial representatives.

ZUSAMMENFASSUNG (ABSTRACT)

Bei der Durchführung einer quantitativen Risikoanalyse (chemical process quantitative risk analysis - CPQRA) verfahrenstechnischer Anlagen kann der Human Factor (HF) durch den Ansatz der menschlichen Zuverlässigkeitstechnik (human reliability analysis - HRA) berücksichtigt werden. Eine der wichtigsten Aufgaben dabei ist die Bestimmung der Wahrscheinlichkeit eines menschlichen Fehlers (human error probability – HEP), um das bestehende Risiko korrekt abschätzen zu können.

Das größte Problem dabei besteht jedoch in den starken Unsicherheiten, mit denen diese HEPs belegt sind, wodurch nicht die realen Bedingungen der betrachteten Anlage bzw. des betrachteten Systems zu Grunde gelegt werden. Es ist jedoch für die Berücksichtigung des HF bei der Durchführung einer QRA von grundlegender Bedeutung, dass mögliche menschliche Ursachen von Ereignissen und Unfällen umfassend identifiziert und quantifiziert werden. Somit wird eine systematische Methode benötigt, mit deren Hilfe einzelnen HF- Faktoren, welche zu einem Unfall führen können, analysiert werden können. Dafür wurde zunächst eine qualitative Methode, zur Bewertung des Human Factors einer verfahrenstechnischen Anlage entwickelt. Diese stellt eine Grundlage für die Integration des HF in die Risikoanalyse dar. Es wurde eine umfangreiche Kategorisierung aller Faktoren, welche die Leistung des Bedieners beeinflussen, erarbeitet, um die realen Bedingungen, welche zu Fehlern führen können zu identifizieren. Diese Faktoren werden auch dazu verwendet, die bestehenden HEPs und die von Experten abgeschätzten Werte abzugleichen.

Die Arbeit läßt sich in folgende Schritte unterteilen:

i) Entwicklung einer qualitativen HF- Bewertungs- Methode. Diese beinhaltet die gesamte Bandbreite des HF und kann angewendet werden, um die HF- Qualität einer bestehenden Anlage abzuschätzen.
ii) Entwicklung einer Kategorisierung um „human error“ Ereignisse zu identifizieren und die organisatorischen Faktoren hinter diesen Ereignissen zu analysieren.
iii) Quantifizierung der einzelnen HF- Faktoren für die quantitative Risikoanalyse. Dabei wurde die Gewichtung der Faktoren durch eine ausführliche Expertenbefragung vorgenommen.

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1 BACKGROUND

1.1 Introduction

Accidents in the chemical and petro-chemical industries around the world have resulted into major consequences. This includes loss of life, property damage and environmental destruction. However, in the last two decades the number of major accidents has significantly decreased. This may be attributed to all the innovations and improvements realised during this time. But still the cost of accidents in terms of lives, injuries and assets remain high. As a result, efforts to reduce the rate of accidents are taking new dimensions within the chemical process industry.

Many major accidents have been attributed to human error as a primary cause. Statistics show that in the chemical process industries accidents attributed, at least in part, to human error range between 60–90% (Joschek, 1981; McCafferty, 1995) and in the petrochemical industry e.g. oil refineries where automation is very high, human error accounts up to 50% (HSE, 1999). Actually it is evident that the relative number of accident events due to human errors is on the rise while those due to technical failures are decreasing. This is contributed by two factors. First is that much emphasis has been laid on improvement of technical design. Most designers are interested in developing process plants with high equipment reliability. Therefore hazards arising from the technical failures dominate risk analysis. Yet, safety of a process plant is influenced by the quality of design, operational and organisational factors. To improve safety and therefore reduce undesired events requires designing of equipment, operations, procedures and work environments in such a way that they are compatible with the physical and cognitive capabilities and limitations of human beings. It involves identifying unrealistic demands on operators and maintainers by system characteristics (Löwe and Kariuki, 2004b). For a plant to be fully developed safety-wise, significant benefits must be provided to those who operate it. Therefore it is important to fully understand all aspects of the facility that influence operator performance. The evaluation and assessment of these aspects fall under the human factors domain. Technical, management and human factors should closely work together to improve performance of a plant. Systems that do not adhere to this are doomed to failure because of unjustifiable demands to the facilities and operators that easily lead to unsafe situations. Secondly, most of the work on human error focuses on symptoms of human error rather than the underlying causes (Vuuren et al., 1997). The percentage range given above (60 – 90%) has evidently a large distribution. This may be explained by uncertainties in what constitutes human error.

Some analysts mostly in accident investigation attribute accidents solely to operator error. They regard human error as failure of frontline operator to perform an action correctly or to omit the action. This approach is not only wrong and naive but also overly simplistic. It is like identifying symptoms of a disease without examining the underlying cause or further defining the disease. After all it is established that in most systems today, a single cause does not lead to an accident.

Literature review shows that a lot of work has been done on human error analysis and human error prediction but as mentioned earlier it concentrates on the unsafe behaviour of the frontline operator. Human Reliability Analysis (HRA) deals with deviation of numerical human error probabilities for the use in fault tree analysis (AIChE, 1994). Absolute quantification in HRA tends to be biased against the actual source of active/direct human error or commonly known as operator error. Moreover, the available HRA data is plagued with uncertainties. Unless we understand all these indirect factors that lead to direct human error there are slim prospects of reducing accidents or incidents caused by operator errors. This calls for a more systematic and comprehensive method for identifying the causal sequence of human error event that would enable development of sound intervention strategies.

1.2 Scope and objective

This study is founded on the above-mentioned premise that most chemical process incidents reports attribute most accidents to human operator. The assumption is that most accidents are preventable through individuals; people choosing to behave safely or otherwise. There is little interest on the underlying causes of errors that lead to accidents. The figure 1-1 shows how the causes of accidents are regarded as opposed to the actual situation. Over the years analysis of risks has concentrated on equipment or the technical aspects of a system yet this is the least contributor of unwanted events when compared with organisation and the operator.

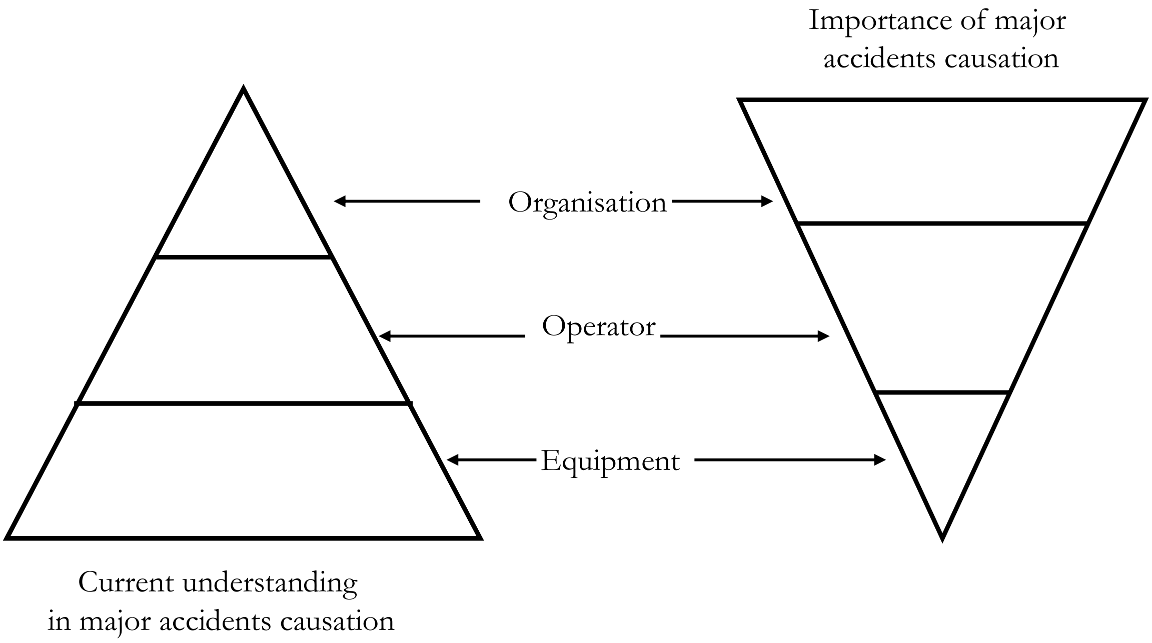

Figure 1-1: Importance of accident causation and the current understanding of actual causes

The objectives of this study as a whole are:

i) To develop a human factors classification and evaluation model.

ii) To develop a framework to identify human error events and to analyse the human and organisational factors behind these error events. This information is critical in establishing the influence that impacts indirectly yet powerfully on the probability of an accident.

iii) To quantify the human and organisational factors for quantitative risk analysis (QRA).

The study covers largely errors classified as slips and lapses. Acts of sabotage are considered out of scope because these involve wilful disregard of laid rules and procedures. The data and information used come from the chemical process and petro-chemical industry. But in some cases, where tasks conditions are thought to be similar data from nuclear, aviation and military areas may be used.

2 LAWS, REGULATIONS AND GUIDELINES IN EUROPEAN CHEMICAL INDUSTRY

It has been realised that human is the weakest link in a system. Incidents due to human contribute significantly to process risk. Therefore a number of laws and guidelines have been put in place to try and contain the situation.

2.1 Council Directive 96/82/EC (SEVESO II)

A spell of major industrial accidents in mid-70s e.g. Flixborough (UK in 1974) and Seveso (Italy in 1976) led to an increase in societal concerns about the safety of chemical process plants. SEVESO Directive 82/501/EEC was issued with the aim of reducing these concerns. The directive was focused on technical measures aimed at reducing the likelihood and the impact of low probabilities high consequences (LP-HC) process accidents on people, property and environment outside the boundaries of the operating sites.

The continued occurrence of catastrophic chemical process accidents (Bhopal, Basel among others) even after SEVESO directive led to a review of the wide belief that LP-HC accidents were mainly due to technical failures. This led to a new paradigm, that the prevention of low probability high consequence accident requires not only appropriate technical practices but also effective management systems because deficient management systems are the root causes of most chemical process accidents (ILO, 2001). Based on this background SEVESO II directive (Council Directive 96/82/EC) was adopted in 1996. The directive emphasises that the operating facility should put in place effective safety management systems as a key measure against major accidents (EU, 1996).

In the preamble of SEVESO II directive it is stated that:
"Whereas analysis of the major accidents reported in the Community indicates that the majority of them are the result of managerial and/or organisational shortcomings; whereas it is therefore necessary to lay down at Community level basic principles for management systems, which must be suitable for preventing and controlling major-accident hazards and limiting the consequences thereof"

SEVESO II was actually the first regulation to introduce checks on the role humans play on the chemical process safety. By introducing the role of management in the accident prevention loop, the directive recognised that the interaction between humans and the system play a vital role on the overall safety of process plants. Article 9 section 1(a) states that member states shall require the operator (operating company) to produce a safety report for the purposes of "demonstrating that a major-accident prevention policy and a safety management system for implementing it have been put into effect in accordance with the information set out in Annex III."

Annex III: (c) the following issues shall be addressed by the safety management system:

(i) Organisation and personnel - the roles and responsibilities of personnel involved in the management of major hazards at all levels in the organisation. The identification of training needs for such personnel and the provision of the training so identified. The involvement of employees and, where appropriate, subcontractors;

From Annex III the following aspects are notable; organisation, training, safety management systems and employees. These as we are going to see in the later chapters are core aspects of human factors. Against this background it will be reasonable to conclude that SEVESO II directive has laid a solid foundation for inclusion of human factors in accident prevention strategies.

The implementation of SEVESO II directive in Germany is done through the *"12. Verordnung zur Durchführung des Bundes-Immissionsschutzgesetzes (Störfall-Verordnung – 12. BImSchV)"* of 26 April 2000. In this law "necessary safety-relevant precautions to avoid false operation", "suitable operating and safety applications", as well as "training of the personnel" are explicitly mentioned as required means to prevent major accidents.

An interpretation of this directive is represented as an accident causation and prevention model, see Fig 2-1.

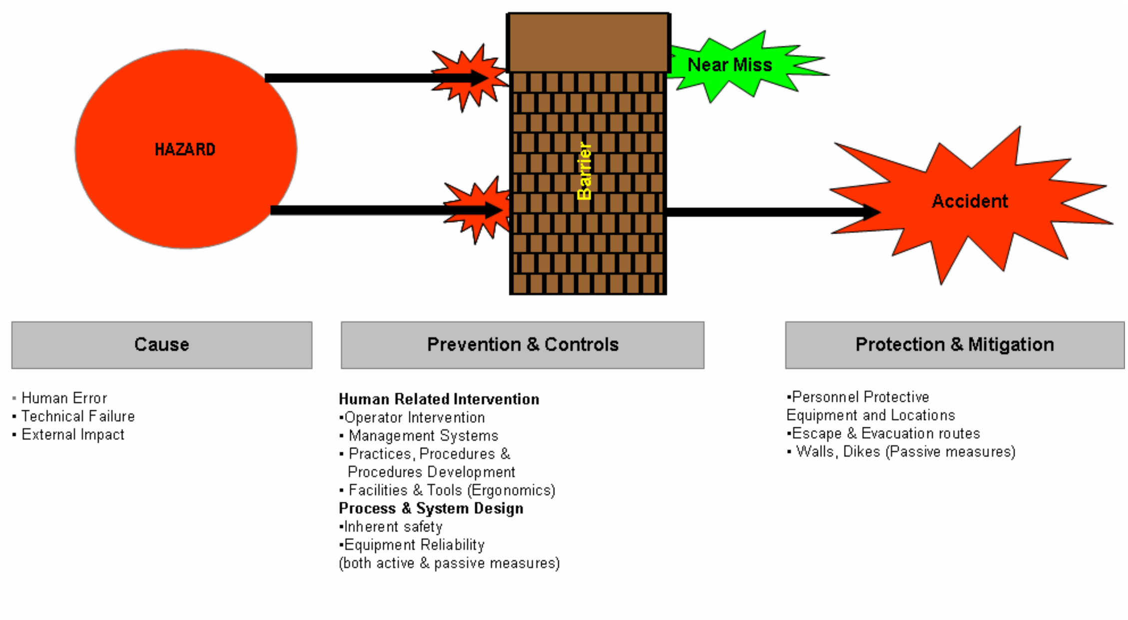

Figure 2-1: Accident causation and prevention model (Kariuki and Löwe, 2005)

This model is the basis of human factors analysis as required by the directive. Hazards identification and evaluation procedures should be applied to all relevant phases of a project including incidents arising from technical failure, external events and human factors. This has been emphasised by Steinbach (Steinbach, 1999) in the life cycle model of a chemical process. The same author has indicated that organisational measures should be applied as a way of controlling process deviations.

2.2 Health and safety laws

There are a number of general laws available within the European Union aimed at promoting workers health and safety. These laws are not directed at any particular industry and are designed to prevent and control minor accidents. The industries that lie out of scope of this law are transport, temporary working sites and extraction. They focus on minimising exposure of workers to risks caused by physical agents.

i. Council Directive 89/654/EEC

This general directive concerns the minimum health and safety requirements for the workplace to ensure better level of protection of the safety and health of workers.

ii. Council Directive 2003/10/EEC

It covers minimum health and safety regarding the exposure of workers to the risks arising from noise.

iii. Council Directive 2002/44/EC

It covers minimum health and safety regarding the exposure of workers to the risks arising from vibrations at workplace.

iv. Council Directive 92/58/EEC

It is about the minimum requirements for provision of safety and/or health signs at work.

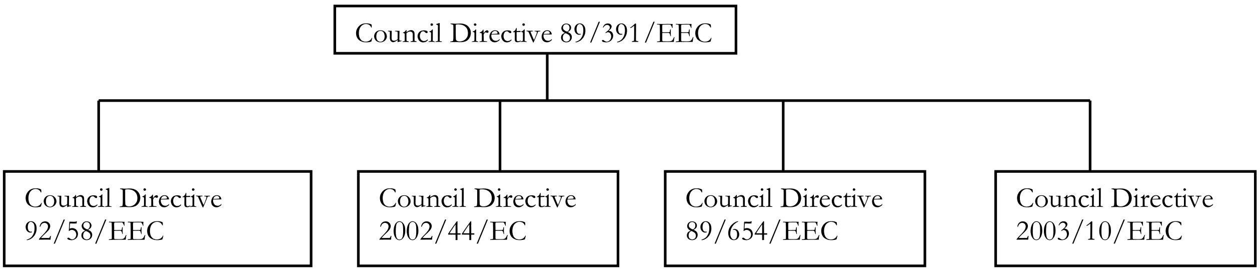

Figure 2-2: European council directive on health and safety

There seems to be sufficient laws and regulations aimed at preventing both minor (those involving employees at work) and major accidents (those with consequences that go beyond the facilities boundaries). Yet, they have not been able to effectively contain the number of accidents occurring in the chemical process industry. One explanation would be that there are no guidelines on how to implement these laws. Operating companies set up safety management systems based on their internal capabilities.

3 FUNDAMENTALS OF HUMAN ERROR

3.1 Different views of Human Error

3.1.1 Traditional Safety Engineering View.

Traditional safety engineering is the most commonly used model in the chemical process industry (CPI) and most other industries (AIChE, 1994). The approach assumes that human error is primarily controllable by the individual (operator), in that people can decide to behave safely or otherwise. It focuses on active errors rather than latent conditions. Active errors are those that the consequences are noticed immediately an error is committed while latent errors take long to manifest themselves. This approach emphasises much on behavioural change through motivation (safety campaigns), disciplinary actions and training. It has been widely used in the area of occupational safety (1st tier risk) to prevent worker injury. Due to its narrow focus it has failed to make an impact as a sufficient technique for analysing human malfunctions in the process safety (2nd tier risk) which emphasises on major process accidents.

In addition, the traditional engineering view takes human error the same way an engineering component fails. Implying that human error is the likelihood that human fails to provide a system function when called upon (Meister, 1966). Human errors are divided into two broad groups (Meister, 1977 ; Swain and Guttman, 1983) namely:

Errors of Omission

- Operator omits the entire task or a step in the task

Errors of Commission

- Include errors of selection, sequence, time (too early or too late) and qualitative (too much or too little).

The inadequacy of this approach is that it concentrates on the observable consequences of an error rather than on its causes. Human error is a consequence not a cause (Reason, 1990) and once identified a search for the causes is required. Its focus on behavioural change closes out consideration of other causes of error such as inadequate design, procedures, supervision and so on. It ignores the underlying error causes or error mechanisms and this means that information on error inducing conditions is rarely fed-back to those responsible in developing remedial measures.

3.1.2 Cognitive View

The main feature of this approach is the assumption that the operators mind can be conceptualised as an information processing system. Human beings are not treated in the same way as a pump or valve. It emphasises that people impose meaning other than the information they receive and their actions are almost always directed to achieving some explicit or implicit goals. The major advantage of this perspective is that it provides an effective classification system of errors in CPI operations from several points of view. By grouping errors of the same type it is possible to develop quantitative database of error frequencies (AIChE, 1994), which has been very elusive over the years.

The most commonly used theory in the discussion of psychological precursors of human error is Generic Error Modelling System (GEMS) (Reason, 1990). This model is based on Rasmussen's Skill-, Rule-, and Knowledge-based (SRK) classification of information processing involved in industrial tasks (Rasmussen, 1981; Rasmussen, 1983). This SRK classification system is discussed further in (Goodstein et al., 1988), (Sanderson and Harwood, 1988) and (Wiegmman and Shapell, 2003).

SRK-based information processing refers to the degree of conscious control by the individual over his or her activities. The lowest level is skill-based and mainly applies to mainly automatic execution of actions, which there is virtually no conscious monitoring. These actions are feed-forward and are initiated by a specific event e.g. an alarm or a procedure that prompts the operator to actuate a valve. In highly practised operation of valve actuation the execution will proceed without conscious thought. This case applies to very many operations in the CPI where the operators are highly experienced.

Rule-based level is related to planning and execution of actions. It is similar to skill-based level in that it is feed-forward but is governed by internal rules that are activated by "signs". The signs are environmental or situational characteristics that fulfil the conditions for the application of the rule; if <condition> then <action>. This means that the characteristics should be made to present themselves in the clearest way. It is mostly applicable in the design of alarms and displays.

The knowledge based level is related to planning of the action. It is different from both rule- and skill-based levels because it is feedback controlled. In this level the operator carries out a task in an almost completely conscious manner. It is common in situations where the operator is a trainee or where an experienced process operator is faced with a completely novel situation. The level is activated in problem solving situations that are unique or completely new to an operator and for which he has no specific rules available. These situations are mainly found in abnormal operating conditions. The operator exerts considerable mental effort to assess the situation and therefore the response action would be slower. Also after each control the effects are studied before further actions are executed. It is therefore important to minimise tasks that calls for this level. The SRK classification is shown in Figure 3-1.

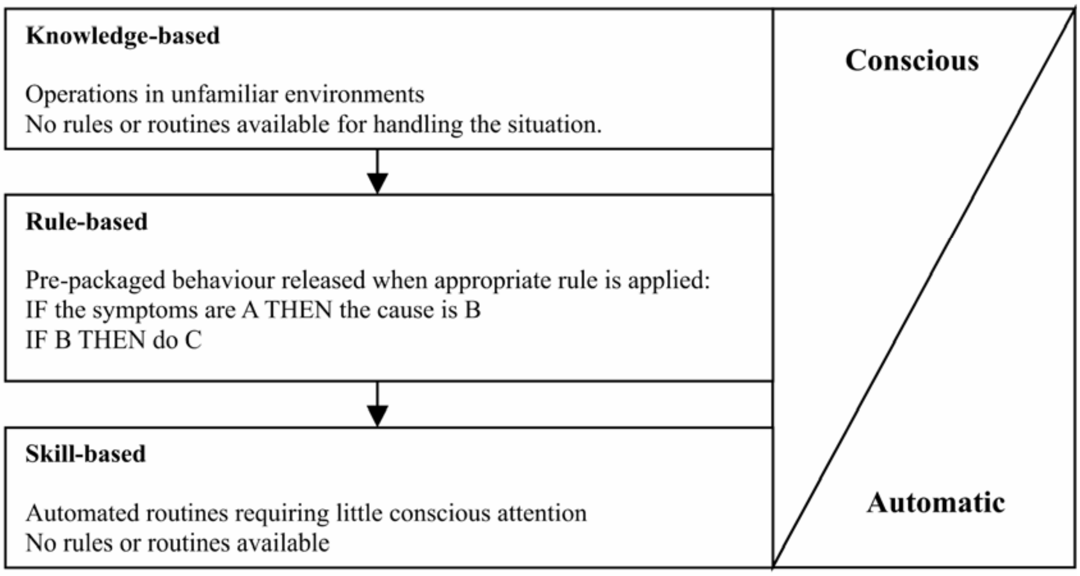

Figure 3-1: The continuum between Conscious and Automatic Behaviour: Adapted from (Reason, 1990)

3.2 Classification of human errors from the cognitive view

The classification on Figure 3-2 is based on causes of human errors related to SRK-based concepts. Mistakes occur by perfect execution of a wrong plan and are therefore very hard to diagnose (Groeneweg, 2000). They occur during the planning stage and are characteristically present on the rule- and knowledge-based cognitive levels. Ruled-based mistakes could occur, for example, when an operator assumes that the reactor is operating perfectly based on pressure/temperature indication that is actually faulty. This condition will lead the operator to make inappropriate diagnosis. On the other hand, a knowledge-based mistake is lack of expertise. Sometimes the operator may be faced with considerably high demands that exert a lot of pressure on the information processing capabilities and this affects the performance of the task especially if problem solving from first principles is required. For instance, the operator may fail to diagnose the cause of a severe abnormality given time-pressure.

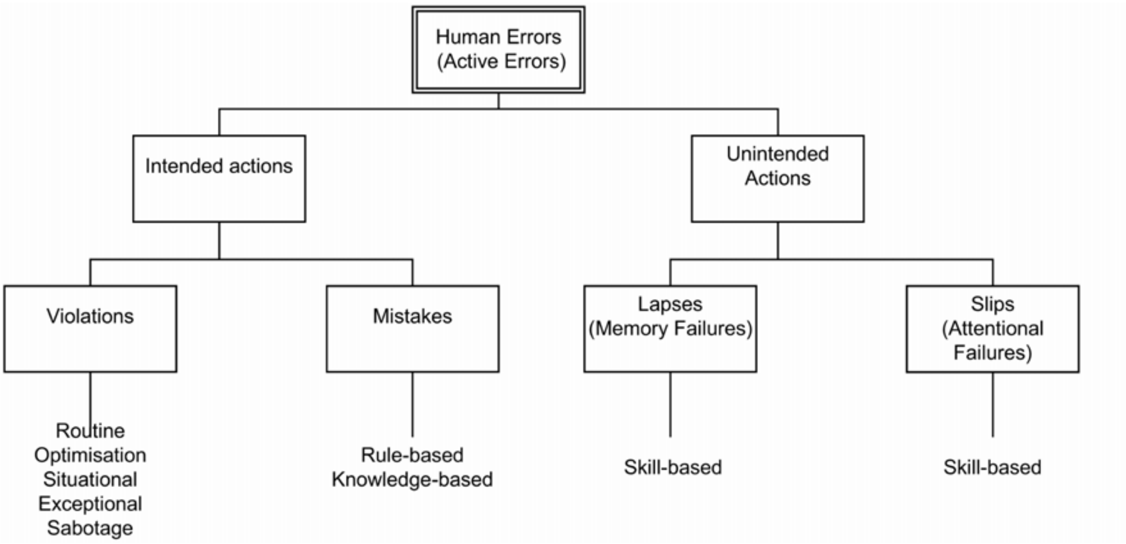

Figure 3-2: Classification of Human Errors (Reason, 1990)

Lapses occur as a result of storage failure and are often termed as “forgetting state” or “confused state”. They are internal and are associated with memory failure. Lapses occur when the situation awareness is blocked (Groeneweg, 2000). Slips on the other hand relate to observable actions associated with perceptual or attention failures. Slips have nothing to do with the validity of the goals set up for the particular action, they are simply errors committed when trying to attain that goal, right or wrong. (Reason, 1990) summarized the classification as follows: mistakes are linked to the planning stage, lapses to storage stage and slips to the execution stage.

The cognitive classification of errors in CPI is not common and therefore statistics do not exist. But looking at the aviation industry it is estimated that 52 % of all errors are “mistakes” while lapses and slips contribute to 30% and 10% respectively. SRK-based levels have shown that rule- and knowledge based are affected very much by the work environment, which makes it reasonable to say that most of the errors are preventable. Lapses are also to some extent influenced by the work environment.

In aviation industry, cognitive approach has produced positive results in identification of cognitive errors and in turn allows the identification and development of effective intervention and mitigation strategies (Wiegmman and Shapell, 2003). The interventions are targeted to the pilot (operator) information processing capability. They strive to improve the information processing through improved procedures, training and use of checklists. They furthermore facilitate information processing by reducing mental overloads and task demands during both normal and upset conditions and thereby reducing potential for errors and accidents.

However, cognitive models are faced by a number of limitations. Firstly, they do not address contextual related factors such as equipment design or environmental factors such as temperature, noise etc. These models also overlook the effects factors like fatigue, illness or motivation affects the operator. Another weakness is the focus on the human information processing capability. Consequently, it encourages the view that focuses on the operator as being the main cause of errors. This ignores the underlying fact that the operator has little or no control over.

3.2.1 Human Factors Engineering View

From this approach operator error is seen as a consequence of mismatch between the demands of a task and the physical and mental capabilities of an individual or an operating team. It is also referred to as "systems view/approach" and it rarely considers humans as the sole cause of error. According to (Heinrich et al., 1980) and (Itoh, 2004), human performance involves a complex interaction between several components of system and operator.

(Edwards, 1988) proposed the SHEL model, which describes the components necessary for man-machine integration and system design. SHEL is acronym for software, hardware, environment and livewire, see Figure 3-3.

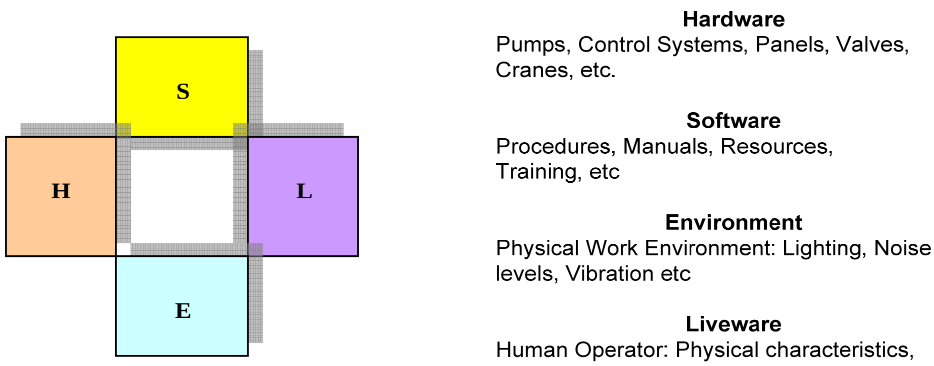

Figure 3-3: The SHEL Model (Edwards, 1988)

The original SHEL model did not contain management component and this was introduced by (Kawano, 2002) and renamed it m-SHEL. Another model was earlier proposed by (Firenze, 1971), which predicts that system failure occurs when there is a mismatch between the human, machine and/or the environment. Therefore as a means to reduce accidents the focus must be on the whole system and not only on the operator.

This approach has a clear advantage over the models discussed earlier. It considers a number of task-related and contextual factors that affect human performance and these include human-machine interface design, optimisation of the working environment and workplace/ job design. This approach is easier and more practical to adopt for people especially engineers with no formal training in psychology or human factors. It has achieved a lot of success in the design of new systems.

Nevertheless, it has limitations. Mostly only external causes of errors are taken into consideration. Since the model focuses on the interaction between components, much emphasis is directed to the design of man-machine interface and anthropometric requirements of task and human characteristics. This view may however mislead in a way to believe that all errors can be designed out. The internal information processing which leads to errors in the area of problem solving and diagnosis can only be covered by cognitive approach (AIChE, 1994; Wiegmman and Shapell, 2003). The approach also fails to provide a systematic framework for addressing underlying causes of errors. Social and organisational factors do not receive the weight they deserve as causes of human errors. The following section describes a model that is proposed for this work.

3.3 Integrated Human Factors Approach

Due to the limitations of the methods discussed earlier a model that takes into consideration all the perspectives of human error is required. Most important is a framework that is able to unearth most if not all underlying causes of human error. The model that will be used is a detailed accident causation model. It explains how an accident propagates and the factors that directly and indirectly influence it.

3.3.1 Human Factors Definition and Background

As indicated in the introduction, statistics show that human failure is a major cause of undesired events in process industries. However, the role insufficient design plays towards these incident causations and the contributions the management failures have towards human error occurrence are not often considered.

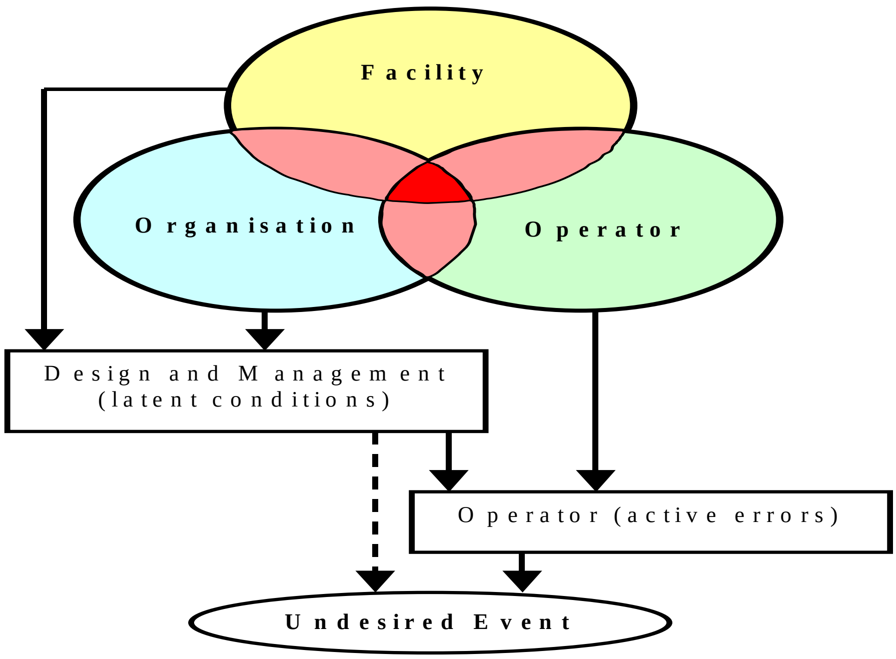

Figure 3-4: Human Factors contribution to undesired events

To sufficiently address human failure a human factors approach is necessary. Human factors refer to environmental, organisational and job factors, and human and individual characteristics, which influence behaviour at work in a way that can affect health and safety (HSE, 1999). It takes human as an integral part of plant design and procurement from the earliest stages. Figure 3-4 (Löwe and Kariuki, 2004a) shows that an undesired event is as a result of latent conditions and active errors. Latent conditions do not immediately affect the functioning of the system but in combination with other factors like active operator error and/or a local trigger (high temperature, high pressure) they could result to a disaster. Latent conditions are results of less-than-adequate design and management decisions.

3.3.2 Integrated Human factors Model

Figure 3-5 shows the integrated human factors model. An undesired event is caused by equipment failure, human error, external impact (not included in the figure) and a combination thereof. These are referred to as direct causes. The science of analysing equipment reliability and failures has developed over the years. Many methods are in existence but none will be discussed here because they lie outside the scope of this work.

Inadequate design implies that the physical and cognitive capabilities and limitations of populations of people are not incorporated into design and operation of a system, process, or equipment. In this case technical design refers to human factors engineering/ human engineering. This branch of engineering is concerned with designing of products, processes and equipment used in manufacturing so as to maximise their ability to be used comfortably, safely and effectively by human beings (Chapanis, 1986). Areas that are considered are workplace layout, workplace accessibility, controls and displays, workplace environment and labelling and signage. These areas are addressed using the human factors engineering approach described earlier. Management faults include inadequate training, procedures & procedure development, work schedules, staffing, shifts & overtime among others. From Figure 3-5 it can be seen that management faults influence equipment failure, human factors engineering and operator characteristics to some extent. An organisation, through formulation of policies and safety culture has also a direct influence on the way a company manages its safety systems. This also affects the performance of the operator.

Organisation, management systems and facility design, when inadequate, are the causes of latent conditions (Reason, 1990). Latent conditions do not immediately affect the functioning of the system but in combination with other factors like active operator error and/or a local trigger (high temperature, high pressure) they could result to a disaster. On the other hand active errors manifest themselves immediately they are committed. If not recovered they could lead to undesired events (accidents or near-miss). Active errors could be analysed using the cognitive approach. Equipment failures can be analysed through plant condition or maintenance and inspection management.

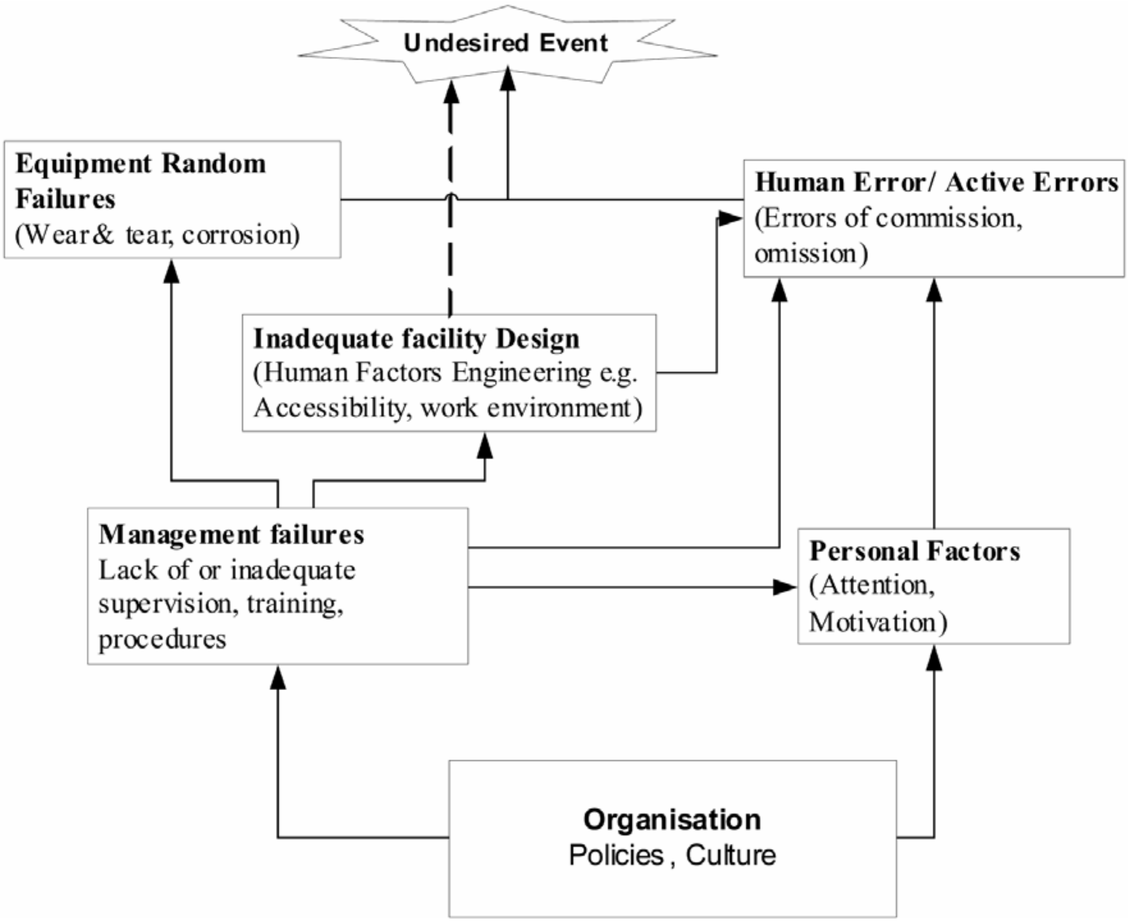

Figure 3-5: Integrated Human Factors Model (Kariuki and Löwe, 2006)

3.4 Accidents Attributed to Human Errors

Most of the major accidents that have occurred over the years have put blame on human error. It is without doubt that human is the biggest contributor of unwanted event. (Turner, 1978) described human as the weakest link in any engineering system. This is due to the fact that all engineering systems rely on human intervention to some extent. Expert systems which handle a wide variety of situations without operator interventions have been on a continuous development. These will however take a long time before they can be totally relied upon .

Some of the tasks that require continuous operator intervention or participation include sequential control, starting of pumps, motors, mainly in batch processes; monitoring the proper operation e.g. watching a filling process; alarm response and diagnosis of unusual system condition (Kandel and Avni, 1988). The accidents described here demonstrate that human error is not only those operator intervention actions but a series of failures that remain dormant until the time they get activated by a local trigger e.g. a rise in pressure or temperature. But it should not be misunderstood that immediate causes (due to operator) are less important than the underlying causes. Immediate causes can only help prevent a previous accident from happening again but underlying accidents may prevent similar accidents (Kletz, 2001).

3.4.1 Piper Alpha

Piper Alpha disaster remains one of the biggest tragedies of the modern times. The disaster happened on 6th July 1988 and claimed 167 deaths. Without deep analysis the disaster could be attributed to "human error" due to the fact that a critical redundant pump had been switched off for repair. Piper Alpha disaster is a perfect example of how lethal human and organisational factors can be.

Risk analyses in offshore structures often focus on structural and equipment reliability (Pate-Cornell, 1993). The soft aspects of safety management which include human factors are not given the weight they deserve. After the investigations of Piper Alpha it was discovered that the pump that had been turned off was a failure of "permit-to-work" system that did not ensure proper communication. This is one of the chronic problems that lead to series of undesired events on the platform. This accident will be analysed with special emphasis on human and organisational failures that affected the initiating events.

The accident started with a process disturbance. Condensate pump "B" tripped and the redundant pump "A" was shut down for maintenance. It happened that in the morning shift the pump "A" was out of service to enable change of a pressure valve. This job had not been completed by the morning shift and was pending for the next day. A blind flange was put in place of the pressure valve. A serious communication failure occurred and the night shift was not informed. Investigations revealed that permit-to-work system had failed. Actually two work permits had been produced for the same pump; one from the supervisor for routine maintenance and the other by shift engineer for the PSV 504 (Cullen, 1990).

After pump "B" tripped immediate efforts to restart it began in order not to loose production. The pump failed to restart and therefore the redundant pump "A" became the main point of focus. The night shift engineer found a permit-to-work for the routine maintenance but not that of the pressure valve. The routine maintenance had not begun according to the permit-to-work. This gave a green light to restart pump "A". No one noted the missing pressure valve. The pressure valve location was 15ft high and was actually obstructed.

After pump "A" was restarted about 45kg of condensate were released but went unnoticed. Had they been detected then ignition and subsequent explosions could have been prevented. There were reported cases of false alarms that lead the operator to ignore the critical ones. Monitoring panels in the control room were also found to be inadequately designed. Another thing that could have lead to failure of this early detection is lack of training of the operators on how to handle abnormal conditions.

Prior to the first explosion, gas alarms were received in the main control room but because of the less-than-adequate design of the detector module rack, the operator did not check where they came from.

The propagation of events after the explosion involved general layout, tight spaces and insufficient fire and blast protection. Several factors contributed to the failure of fire fighting capabilities. The automatic deluge system had been switched off by divers. The manual system was located in areas vulnerable to fires and blasts and therefore did not survive the first explosion. There were no redundancies elsewhere. There was only one evacuation route and when this was engulfed by fire the exercise was literally made impossible.

The following human factors can be pointed out from this accident:

Communication: The change of shift was not systematically done. There was failure of communication when writing work-to-permits (two were produced for the same pump).

Supervision: The blind flange that was installed in place of pressure valve was not made leak-tight. Therefore it could not stand the high pressures. There was no inspection after fitting and this could have led to early leaks.

Accessibility: The location of the pressure valve was out of sight for the night shift people. When designing such a critical component then it should not lie beyond reach for the maintainer or operator. The design of manual fire fighting systems also failed to follow the accessibility guidelines.

Alarm design: There were very many non-critical alarms that lead the control operators to ignore the series of alarms after the first explosion. There are guidelines for designing alarms, see PRISM guidelines (PRISM, 2004).

Training: Operators were not trained on upset conditions.

Display design: In the control room the monitoring panels were not clearly visible and one could not easily tell where the alarms originated from.

3.4.2 Texaco Incident

An explosion, followed by a number of fires, occurred on 24th July 1994 at the Texaco oil refinery, Pembroke, Wales. Twenty tonnes of hydrocarbon were released and exploded when a slug of liquid was sent through the flare system. There were 26 injuries and reinstating costs were estimated to 48 million British pounds. There were no fatalities but this was because it was on Sunday. The investigations were carried out by Health & Safety Executive (HSE).

The incident started at around 0900hrs when hydrocarbon flow was lost to the de-ethanizer Figure 3-5 shows a simplified schema of the relevant part to describe this incident (Dykes, 1997). This caused the liquid in the de-ethanizer to empty into the debutanizer and the overhead accumulator vessel. To prevent the total loss of liquid from the de-ethanizer Valve A closed and this was according to the design. When valve A closed it caused a low volume on the de-butanizer and this led to the automatic closure of valve B. The hydrocarbon on the de-butanizer was now blocked-in.

The hydrocarbon in the de-butanizer was still subject to heating. The temperature and pressure rose leading to the opening of the pressure relief valve and the de-butinizer to vent. Thereafter the liquid level in the de-ethanizer was restored and so valve A opened and flow restored to de-butanizer. This should have caused Valve B to open and allow flow of hydrocarbon out of the already pressurised de-butanizer to naphtha splitter. But valve B remained closed while the display to the operator showed that the valve was actually open. The display did not show the global presentation of the process and therefore the operator could not tell whether or not there was hydrocarbon flow to the naphtha splitter.

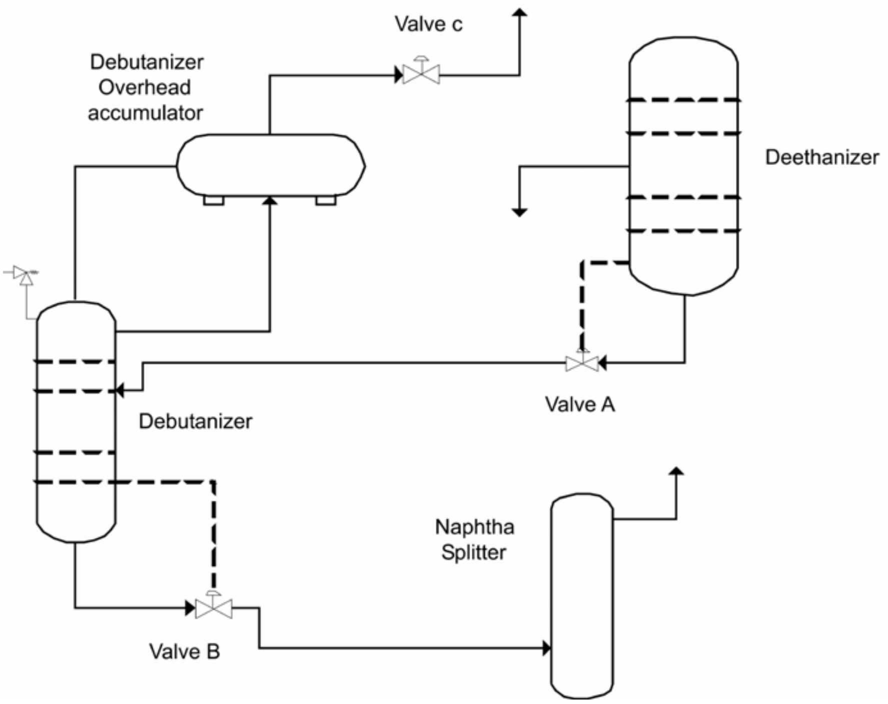

Figure 3-6: Simplified schema for the Texaco plant. Adapted from (Dykes, 1997)

When the operator noticed that the pressure was still building on the de-butanizer he opened valve C to provide another route out of the vessel. This resulted in a high liquid level in the flare stack knock out drum. Due to a previous modification, there was no facility to pump out the knock-out drum quickly.

By the time the operators concentrated on the problems on the de-ethanizer and de-butanizer, they were interrupted and confused by the number of alarms being generated.

The combination of high liquid level in the knock-out drum and the de-butanizer venting into the flare system again, caused a slug of liquid to be carried through the knock-out drum and into the flare, which collapsed at the weak point.

Human factors lessons from this accident could be summarised as follows:

Alarm System: It was discovered that 87 % of the 2040 alarms were classified as high priority despite being only informative. These turned out to be nuisance alarms especially during upset conditions. Safety critical alarms should have been a number that the operator could handle.

Display: The display did not give a complete overview of the process to help the operator easily diagnose the root cause of the problem.

Training and competence: The operators were not trained to check on simple mass and volumetric balances whenever flow or level problems were experienced. There was also no guidance on how to handle emergency conditions and when to initiate shutdowns. In this case operations continued when on the contrary shutdown should have been initiated.

3.4.2.1 Hoechst Accident

This happened in 1993. The incident happened when o-nitrochlorobenzene (o-NCB) was converted with methanol and sodium hydroxide to form an intermediate o-nitroanisole (o-NA) for other reactions. This reaction normally takes place in a stirred tank semi-batch reactor. First o-NCB and methanol are fed into the reactor then the stirrer is started and cold methanolic sodium hydroxide is dosed into the reactor. The reaction is exothermic and when the temperature reached 90^{o}C the cooling system is activated to retain the reaction at a constant temperature for the rest of the reaction. The dosing process takes 5 hours and the reaction is completed after 2 more hours of stirring.

The 1993 incident happened due to three failures. The stirrer was not started from the beginning and this lead to accumulation of reactants in the reactor in two non-mixed phases. Since no reaction was taking place there was no increase in temperature observed. This prompted the operator to use steam to heat the reactor to reach the required reaction temperatures of 90^{o}C. Only then did the operator realise that the stirrer was off and switched it on immediately.

The reaction started immediately and a lot of heat reaction was generated. The cooling system could not remove all of it. At 160^{o}C and 16bar two safety valves opened and the reactants were discharged to the atmosphere through the roof. Part of the products discharged was 28% toxic o-NA.

From this incident the following human factor relevant issues could be pointed out.
Control and displays: Task analysis could have helped to identify that the stirring task was critical. Due to the nature of the task (it is performed at a skill-based level) it was possible to deduce that an operator could easily experience a memory lapse once in a while. An

interlock to block dosage when the stirrer fails or an alarm to alert the operator would have been a viable solution.

Training: The operator did not have basic training on reaction chemistry. This is the reason why he opted to heat the reactor with steam. Training on reaction chemistry would have helped in trouble shooting.

4 CHEMICAL PROCESS QUANTITATIVE RISK ANALYSIS METHODS

4.1 Introduction

Serious accidents are viewed as the culmination of a sequence of failures involving human, hardware or both. It is worth noting that accidents can never be prevented entirely or eliminated. It is often important to reduce their frequencies. A necessary first step in such a risk reduction effort is to be aware of the risks associated with the system in the first place. Chemical process quantitative risk analysis (CPQRA) was developed to facilitate the quantification of risks associated with the complex engineered systems.

This method has been used in high-hazard industries. Its aim is to estimate and quantify risks originating from a hazardous industrial activity to individuals and groups inside or outside the boundary of the plant. It is a probabilistic methodology which has its roots in the nuclear, aerospace and electronic industries. In the nuclear and aerospace industries it is commonly referred to as Probabilistic Risk Analysis (PRA). The basis of CPQRA is to identify incident scenarios and evaluate the risk by defining the probability of failure, the probability of consequences and the potential impact of those consequences.

CPQRA is performed on a company's own initiative and because of the requirement from authorities. One of the regulations that have promoted its use is the Seveso II directive. In the Netherlands it is compulsory to quantify risks as part of an application for operational licences. The Norwegian Petroleum Directorate (NPD) has adopted QRA as an approach to verify that the risk acceptance criteria are met (Nielsen et al., 1996; NPD, 1992). In the UK, high-risk companies are required to provide safety cases similar to CPQRA. This provision is through the Control of Major Accident Hazards Regulation (COMAH) of 1999. It can be said that CPQRA has been accepted in a number of countries in the EU for preparing statements about total risk from an industrial activity. Exceptions are in Germany and Denmark where a deterministic approach is used. CPQRA is only accepted as supporting evidence when choices are to be made amongst different safety solutions (Einarsson, 1999).

4.2 General Approach of CPQRA

Quantitative Risk Analyses are achieved in four broad steps which are hierarchical in nature. These are: Hazard identification, consequences quantification, frequency quantification and risk estimation. The steps are used for structuring the vast quantities of information that go into risk analysis. Quantification will only be possible when a variety of different types of data are available. These include

a) Components failure rate data
b) Common cause failure data
c) Human action data
d) External events data

The summarised procedures for a CPQRA are illustrated in fig. 4-1.

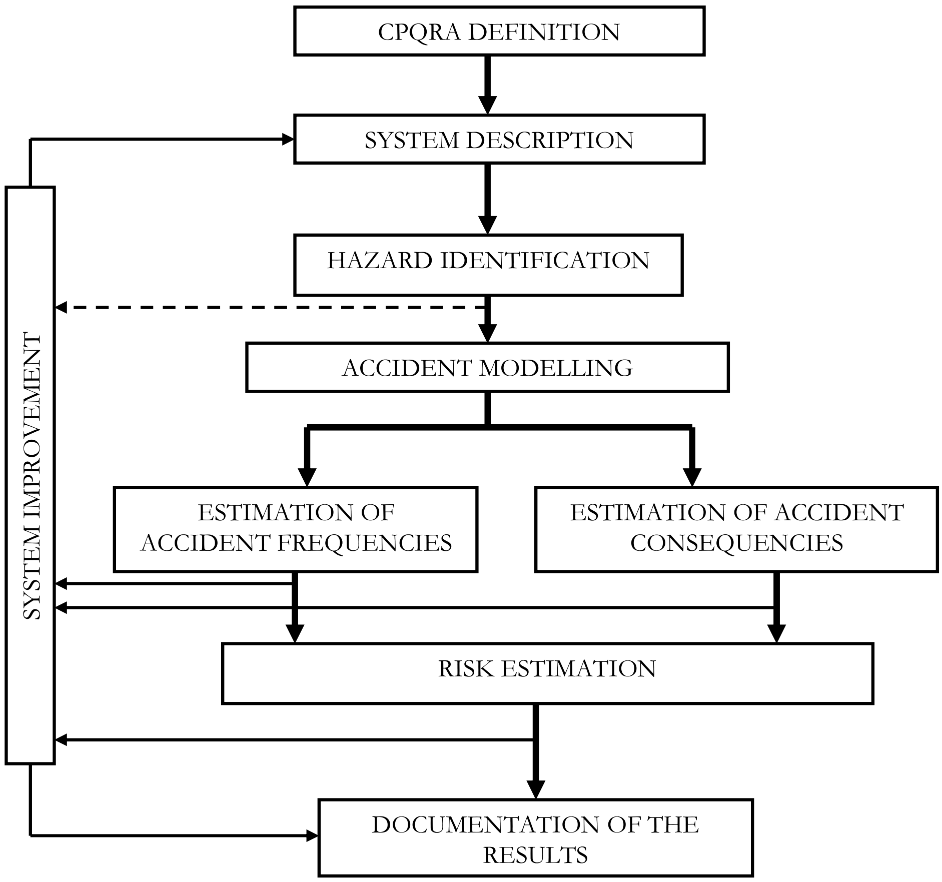

Figure 4-1: Steps for a Chemical Process Quantitative Risk Analysis

4.2.1 CPQRA Definition

QRA identifies those areas where operation, engineering, or management systems may be modified to reduce risk and may identify the most economical way to do it. Therefore, since a complete CPQRA may not always be necessary or feasible on every system, a scope has to be defined in order to satisfy practical budgets, schedules and the defined goals.

4.2.1.1 Depth of the study

The depth of the CPQRA is defined using a "study cube" (AIChE, 2000). The cube contains three axes representing. Risk estimation technique, complexity of analyses and number of incidents selected (fig 4-2).

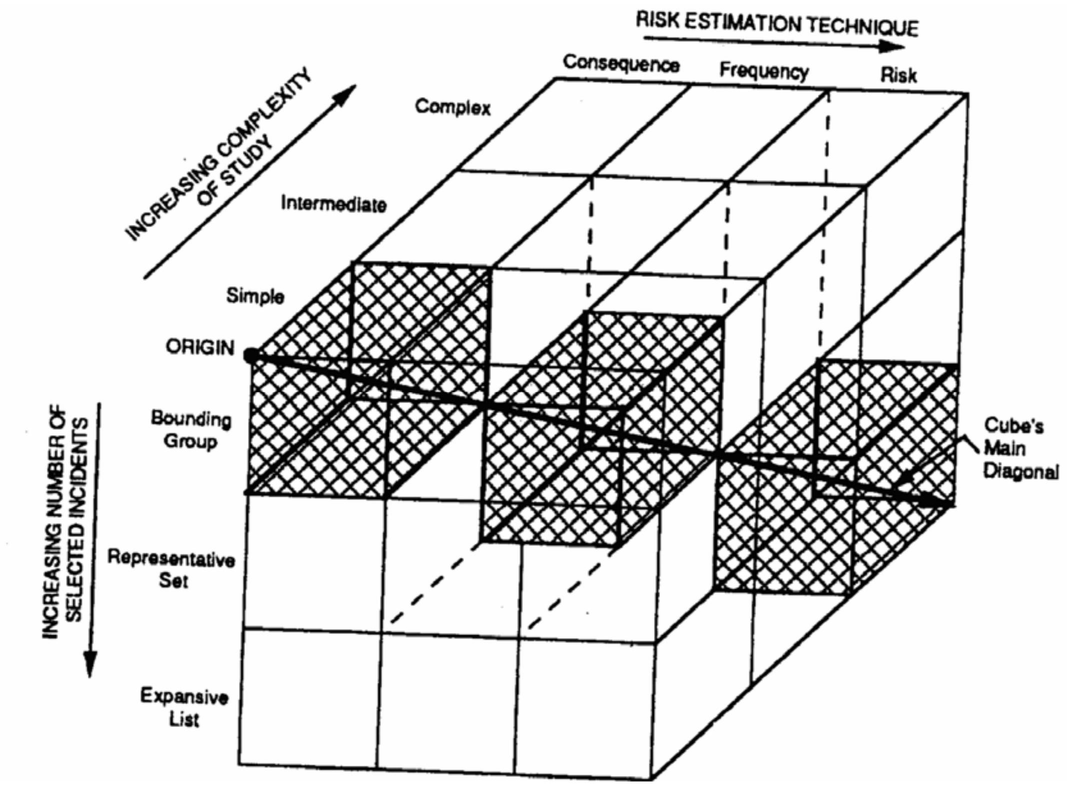

Figure 4-2: The Study Cube (AIChE, 2000)

Risk estimation technique is defined by the nature of results desired during the study. Estimation by consequence, frequency and risk represents the level of maturity of these techniques. Consequence estimation is well understood because it is represented by models like discharge, toxic effect and dispersion calculations. Frequency estimation is more difficult especially where historical data does not exist. Techniques like fault tree analysis and event trees are used to develop such data, but these models are not mature like those for consequences estimation. The technique being developed in this work is applicable during frequency estimation. Risk estimation requires understanding of the demographic distribution at consequence effect zone in case of an accident. It also requires wind flow characteristics and therefore risk estimation with low uncertainty is hard to achieve.

Complexity of the study is defined by the complexity of the models used and the number of incident outcome cases. Study models range from, for example, a simple unidirectional single speed wind to multi-directional, variable speeds with different atmospheric stabilities. Incident outcomes are cases that have potential impact on the population. Therefore the more cases considered the more complex is the study.

On the study cube the number of incident cases is represented by bounding group, representative set and expansive list. Bounding group is concerned with small number of incidents which are potentially catastrophic and usually referred to as worst cases. They would include, for instance, large toxic release or large explosions that affect a large (offsite) zone. Representative set contains some incidents which are potentially catastrophic and some that could be defined as major. Major incidents have a medium effect zone and are limited to site boundaries. Expansive list contains all incidents that have potentially small, major and catastrophic effects.

The depth of CPQRA proceeds across the diagonal of the cube. Simple/consequence is useful for screening purposes. Intermediate/frequency CPQRA is applicable when the design is substantially developed. The maximum benefit is achieved from the basic design phase of an engineering project. Here the frequencies are estimated and modified if necessary. In the complex/risk CPQRA all necessary information on the plant is available. It is possible to achieve this CPQRA only after the detailed design is available. Integration of human factors into CPQRA will produce best results when applied in the intermediate/frequency and complex/risk. This is because it would be possible to carry out compressive task analyses during basic design and detailed design phases.

4.2.2 System Description

This involves compilation of the process or plant information necessary for risk analysis. It covers all relevant design and operational information, which include; piping and instrumentation diagrams (P&IDs), process flow diagrams, operating and maintenance procedures as well as emergency operating procedures and properties of the material being processed among others. Also necessary is the site location and layout, population distribution in the surroundings and weather data.

4.2.3 Hazards Identification

This step involves incident identification, enumeration and selection. The aim of this step is to obtain a general view of potential hazards, to find relevant subsystems for detailed analysis and to obtain a detailed view of hazards and factors contributing to them. As mentioned in section 4.2.1.1 the incidents are screened based on the aim of the study. It is worthy to mention here that representative set is most of the time sufficient for risk estimation to the public. Many tools for this step are available and they include DOW index, checklists, hazard and operability (HAZOP) studies, failure mode and effect analysis (FMEA) and preliminary hazard analysis (PHA). A detailed review of these techniques is found in hazard evaluation procedures guidelines (AIChE, 1992).

4.2.4 Accidents Modelling

Accidents are modelled to gain a deeper understanding of potentially serious accidents and obtain a basis for quantification of accident frequencies. Fault tree and event tree analysis are the most commonly applied techniques used for this purpose. In this step initiating events are identified together with corresponding intermediate events and basic events.

4.2.5 Consequence Estimation

The basis of consequence analysis is the loss of containment of hazardous material. The material is hazardous based on the energy stored and toxic properties. Important models used for consequence estimation are discharge, dispersion and toxic effect calculations. Examples consequences of interest during risk analysis are boiling liquid expanding vapour explosion (BLEVE) and unconfined vapour cloud explosion (UVCE).

4.2.6 Frequency Estimation

Frequency estimation could either be modelled or acquired from historical data. Where historical data is applied the failure rates for components are used. Detailed frequency modelling is not necessary here and therefore could be used at the initial phases of design when plant systems and safeguards are not well defined. An important source of failure rates for the petro-chemical industry is Offshore Reliability Data Handbook (OREDA, 2002). Modelling of frequencies is achieved by use of fault trees and event trees. The relation between the two is illustrated in figure 4-3. The inclusion of human factors in risk analysis, which is the main aim of this work, is at the basic events of the fault tree analysis. This is also shown in the same figure.

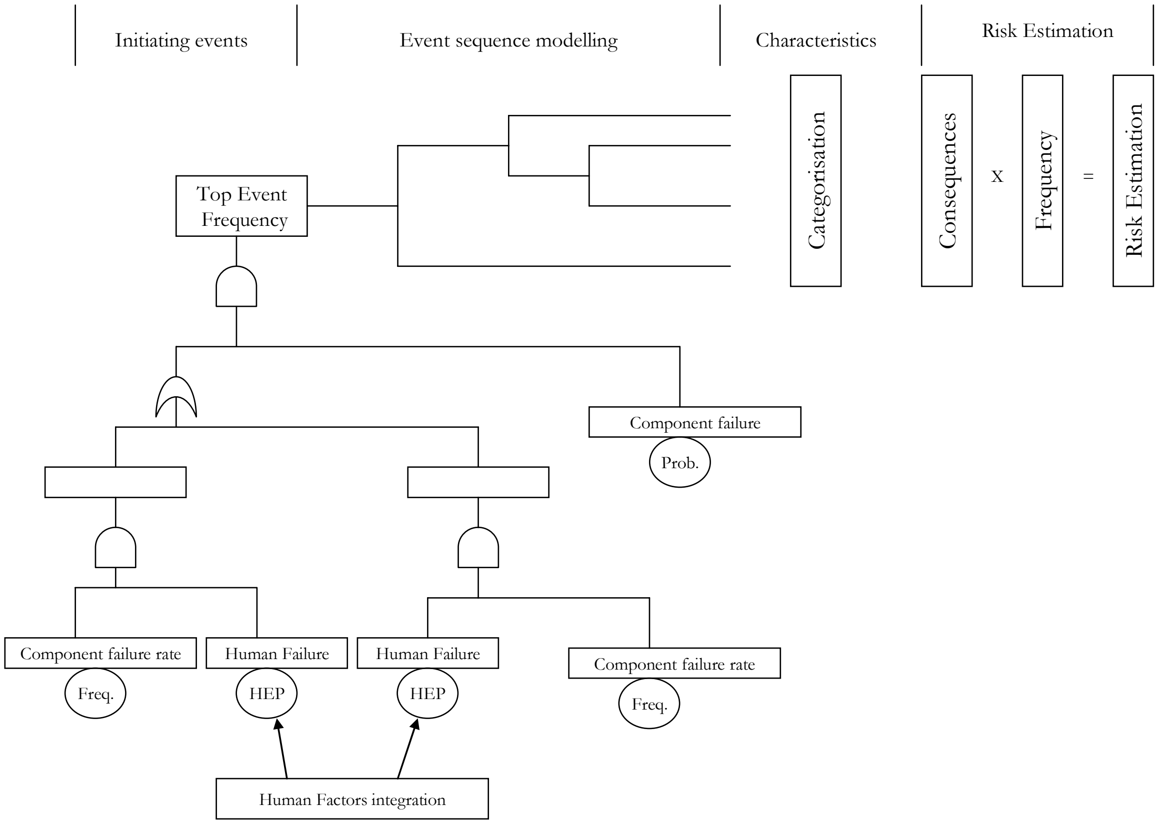

Figure 4-3: Relation between Fault tree analysis and Event tree analysis

4.2.7 Risk Estimation

To estimate risk individual and societal risk approaches are normally applied. Individual risk represents the likelihood of fatality at a particular effect zone. It assumes that each individual on that area has the same chance of being affected. It is commonly represented by contour plots. Societal risk on the other hand estimates the number of people killed by each incident outcome. F-N graphs or curves are common way of representing this type of risks. While estimating risks it is important to know wind distribution directions.

More on QRA/ PRA could be found in the following references: (AIChE, 2000; Bley et al., 1992; NASA, 2002; NUREG, 1983)

4.3 Human Reliability Analysis for Quantitative Risk Analysis

4.3.1 Introduction

Human reliability was described as the probability that a person a) correctly performs an action required by the system within the required time and b) that he does not perform any extraneous act that could degrade the system (Swain and Guttman, 1983). There have been other qualitative definitions e.g. the ability of humans to adapt to changing conditions in disturbances (Hacker, 1998). Methods used to assess human reliability are known as human reliability analysis (Swain, 1990). In carrying out HRA it is necessary to identify those tasks that can have effect on system safety and reliability.

HRA can involve both qualitative and quantitative approaches. In the qualitative approach the human actions are modelled; tasks are analysed and the possible sources of errors identified. In the latter the human error probabilities (HEPs) are assessed and quantification of certain factors is made and this is the most applicable within the QRA framework. There are methods existing for both approaches. Some of them will be discussed here to investigate to what extent they can be applied to investigate human factors.

The central tenet of HRA is that HEP estimation must be reasonably accurate (Kirwan, 1996). This is important to avoid under / overestimation of the actual risk. HRA techniques fall under two categories, those that use a database and those that use expert opinion. The database approach uses a collection of generic HEP that need to be modified to fit the system specific probabilities. This is the main concern of current work. There are many factors that influence the occurrence of human error. Modification of these HEP has mainly been done by trying to consider the context-related Performance Influencing Factors apparent in the scenario being analysed. This is done in a rather unstructured way.

The drawbacks of the current HRA related to this study could be summarised as follows:

- ◊ HRA methodologies are not able to identify various causes of human errors. The observable results of human actions are the main point of focus (Dougherty, 1990).
- ◊ Inadequacy of data for human error analysis (Hollnagel, 1998).

◊ Effects of organisational, managerial and safety cultures are not adequately considered in HRA (Hirschberg and Dang, 1996).

◊ Several methods or models for incorporating human and organizational factors in quantitative risk analyses are described in the literature, like Manager (Pitblado et al., 1990), MACHINE (Embrey, 1992), I-RISK (Bellamy et al., 1999), and ARAMIS (Hourtolou and Salvi, 2004). None of these methods seems to be regularly applied by the industry.

4.3.2 Technique for Human Error Rate Prediction (THERP)

This is the most known and widely used applied technique to perform HRA. It is described in extensive details in (Swain and Guttman, 1983). THERP is a method for predicting HEPs and evaluating the degradation of a man-machine system likely to be caused by human errors, alone or in connection with relevant system characteristics. It is a decomposition technique. The process is as follows:

◊ Decomposition of tasks into elements.

◊ Assigning nominal HEPs to each element.

◊ Estimation of effects of performance influencing/shaping factors (PIFs/ PSFs) on each element.

◊ Modelling in an HRA event tree

◊ Quantification of total task HEP

In the decomposition, tasks are split into sub-tasks. This is because particular tasks may require, for instance, seven operations by more that one operator located at different positions. The task in this case will be decomposed into seven elements and the procedure to undertake such a decomposition is described in the HRA handbook (Swain and Guttman, 1983).

After tasks are sub-divided into subtasks (tasks elements) nominal HEPS are assigned. The THERP Handbook has a set of tables with different human error probabilities for various tasks. The problem occurs when a task does not appear on the available tables. This can be a major reason for occurrence of “outliers” which is task types which are beyond the technique’s ability (Kirwan, 1996).

The determination of the effects of PSFs occurs based on the assessor's qualitative analyses of the scenario. A wide range of PSFs have been given by the same handbook. They include procedures, training, stress, distractions and operator experience among others. The assessor uses a multiplier on nominal HEP. This is usually derived from the error factors (EF) associated with each HEP. EF expresses the uncertainty about the real value of HEP. It is the ratio between the 95^{th} percentile upper bound of the log-normal probability density function and the median (or ratio between the median and the 5% - lower bound).

THERP models depend on different tasks. For instance, a series of identical knobs are to be adjusted to the same set-point. If an operator mistakenly sets the first knob to a wrong point, then the probability that all others are set to the same wrong set-point increases. Models of dependence levels are found in the same handbook. Failing to consider dependence could have dramatic effects on HEPs.

A HRA event tree, see Figure 4-1, is used to model HEPs. It represents a binary decision process, that is, success or failure in task performance as the only possibilities.

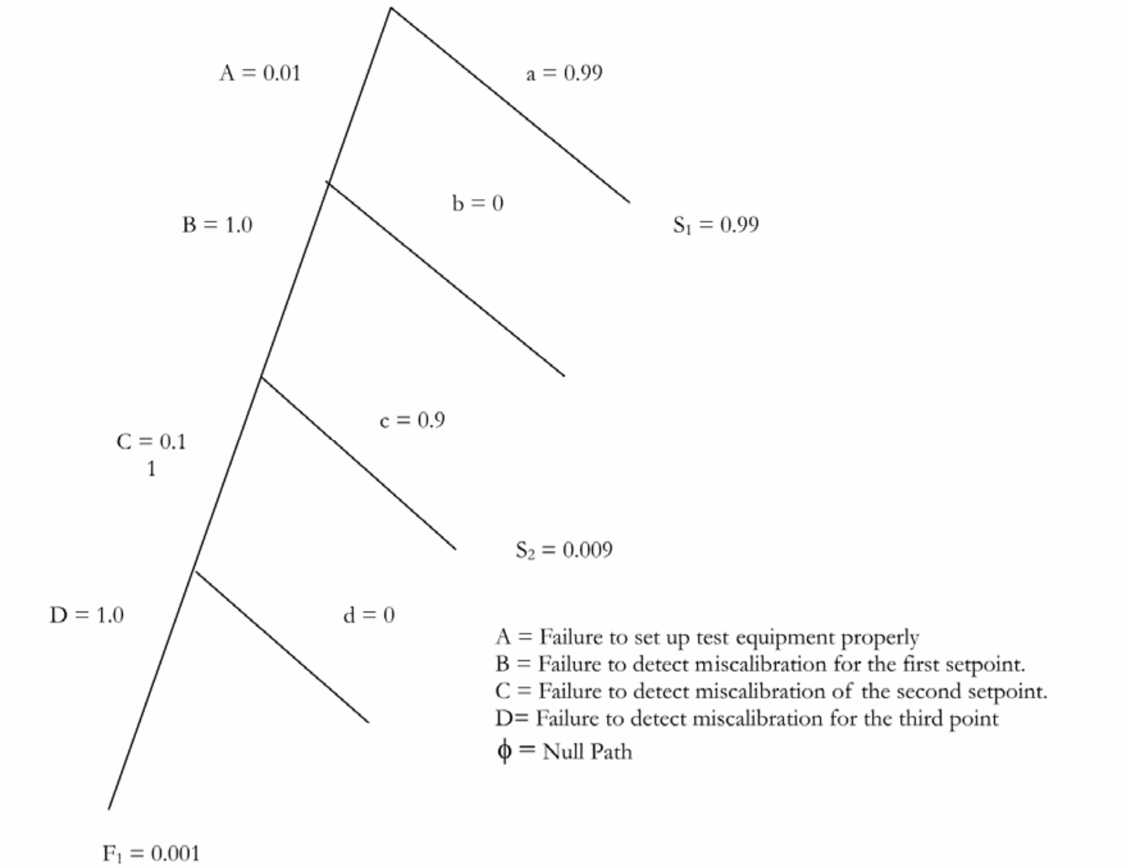

Figure 4-4: HRA event tree. Adapted from (Swain and Guttman, 1983)

The success and failure probability outcomes add up to unity. By using the event tree it is also possible to explicitly show the recovery paths of the errors that are recoverable.

The description above is a brief introduction of THERP. It is not the intention of the author to go into extensive depth because this is available in the THERP handbook. This introductory part is to show that THERP is a powerful technique for modelling HRA but has limitations to be applied in context of the present work. The main limitation of THERP is that the PSF process is relatively unstructured and highly judgmental based on the assessor's experience. In addition there has been a tendency to use stress and time as the only PSFs influencing HEPs. This could be attributed to lack of systematic PSFs analysis and quantification tool. Furthermore, the interaction between certain PSFs is yet unknown, therefore no guidelines can be given for possible combinations. When developing human factors quantification tool, this fact will be taken into consideration as a weakness of THERP. THERP also lays special emphasis on nuclear power plants and some of the conditions are not similar to those of chemical process plants.

4.3.3 Success Likelihood Index Method

The success likelihood index method (SLIM) is a technique that uses expert judgment to develop HEPs. Its premise is that the probability of error associated with a task or a task step is a function of the PIFs in the situation (Embrey et al., 1984). The SLIM procedure numerically rates the PIFs which influence the probability of error, and these ratings are combined for each task to give an index called success likelihood index (SLI). This index is then converted to a probability by means of a general relation between the SLI and calibration tasks (AIChE, 1994).

4.3.3.1 Steps of the SLI Procedure

The calculation of SLI takes place in five distinct steps:

Step 1: Modelling and specification of PIFs

Here tasks are evaluated by judges to try to identify the errors of omission and/commission that could occur. Then PIFs that could have significant effects on these error modes are determined. As an example judges may decide that PIFs influencing success in the task being evaluated are:

- ◊ Time Stress
- ◊ Procedures
- ◊ Experience
- ◊ Quality of information

Step 2: Weighting the PIFs

In the original SLIM a simple multi-attribute rating technique (SMART) was used to estimate weights (Embrey, 1983). Judges are asked to decide which single PIF would have the most significant effect on enhancing the probability of success if it were improved. This is assigned a weight of 100. The PIF which is viewed as the next most significant on success is then chosen and a weight relative to the most significant PIF is assigned to it. It acquires a weight of 50 if the judges feel it is half as important as the first one. This is repeated for all the PIFs. Then the weights are normalised and they represent the relative importance of each PIF in terms of how strongly it influences the likelihood of success.

Step 3: Rating the Task

Ratings represent the expert opinions' regarding the actual situation for the tasks being assessed. The rating is by directly assigning a numerical value to each PSF on a scale of 0–100. If for example procedures are assigned a rating of 50, then that signifies the industry average.

Step 4: Calculating SLIs

The index is calculated by forming the product of the normalised weights and the ratings for each PIF and summing them up. This means that SLI could take any value from 0 to 100, where 0 indicates that the task has a high probability of failing and 100 a high probability of success. The SLI is converted into HEP by the use of the formula:

$$\log HEP = aSLI + b \tag{4.1}$$

The constants a and b are calculated by applying this formula to tasks with known HEPs. SLI for the tasks with known HEPs is obtained using the same procedure described above.

There are limitations associated with SLIM:

a) The weighting method uses one pivot PIF. All other PIFs are weighted in comparison to this particular PIF. It does not take into consideration the interaction between all PIFs being analysed.
b) There exists no guideline on how to give ratings. It solely depends on the assessors' knowledge and experience.
c) SLIM has the strength in analysing PIFs with direct influence on errors. These are procedures, training, time stress etc. but fail to address the higher levels like management.
d) There are inherent theoretical weaknesses associated with the calibration equation (Vestrucci, 1988).

4.3.3.2 Cognitive Reliability and Error Analysis Method (CREAM)

CREAM (Hollnagel, 1998) is classified as the second generation of HRA. It identifies tasks or parts of work that are affected by variation in human cognition. Then it determines the conditions under which the reliability of cognition may be reduced, and where therefore these tasks or actions may constitute a source of risk. The method also provides an appraisal of the consequences of human performance on system safety which can be used in a probabilistic risk analysis (PRA). CREAM is based on a category of eight error modes. These are:

Timing: too early too late
Duration: too long too short
Sequence: Reversal, repetition, commission, intrusion
Object: wrong action, wrong object
Force: too much, too short
Direction: wrong direction
Speed: too fact, too slow
Distance: too far, too near.

This method is proving to be a useful tool in the nuclear and aviation industry where the performance of tasks depends very much on human cognition. It has not, however, been widely accepted in the chemical process industry because the task conditions are different and vary from manual to semi-automated.

4.3.4 Incorporating Human Reliability Analysis into Quantitative Risk Analysis (State-of-the-art)

The main intention of QRA of a complex system is to determine the probability that the undesired event will occur when certain components fail, be they either technical or human and to what extent their consequences will be. HRA discussed above is used to generate the human error probabilities. The approach most applied in incorporating HRA into QRA is by application of fault tree analysis (FTA). FTA is a deductive system analysis where it is postulated that the system itself has failed in a certain way, and an attempt is made to find out what modes of system or subsystem (component) behaviour contributed to this failure (Joschek, 1981; Steinbach, 1999).

The fault tree itself is a graphic model of the various parallel and sequential combinations of faults that will result in the occurrence of the predefined undesired event usually known as the *top event*. The faults can be events that are associated with component technical failures, human errors, and/or external events e.g. an earthquake or floods which can lead to the undesired event. A fault tree thus depicts the logical interrelationships of basic events that lead to the undesired event, the top event of the fault tree.

FTA uses the concept that an outcome is a result of binary combination. Binary AND and OR gates are used to combine the events that lead to top event. In the first instance, FT is a qualitative model but is often quantified to calculate the probability of the top event.

HRA could either be qualitative or quantitative. For the purpose of illustrating the state-of-the-art of HRA in QRA an example is going to be used. This is a case study originally done by (Ozog, 1985) but has been modified to fit this specific situation. The system under investigation is a storage tank which holds a flammable liquid under low positive nitrogen. It is as shown in Fig 4-2. The pressure is controlled by a pressure control PICA-1. In case of overpressurisation, a relief valve RV-1 opens. The liquid is delivered in to the storage tank from tank trucks and is supplied to the process via pump PI-1.

A hazard and operability (HAZOP) study was done and the most serious hazard identified was unrecoverable release from the storage tank. More details on HAZOP can be obtained from (Kletz, 1999). For this event a fault tree was constructed. Only the portion of the fault tree relevant to this study is illustrated in fig 4-3.

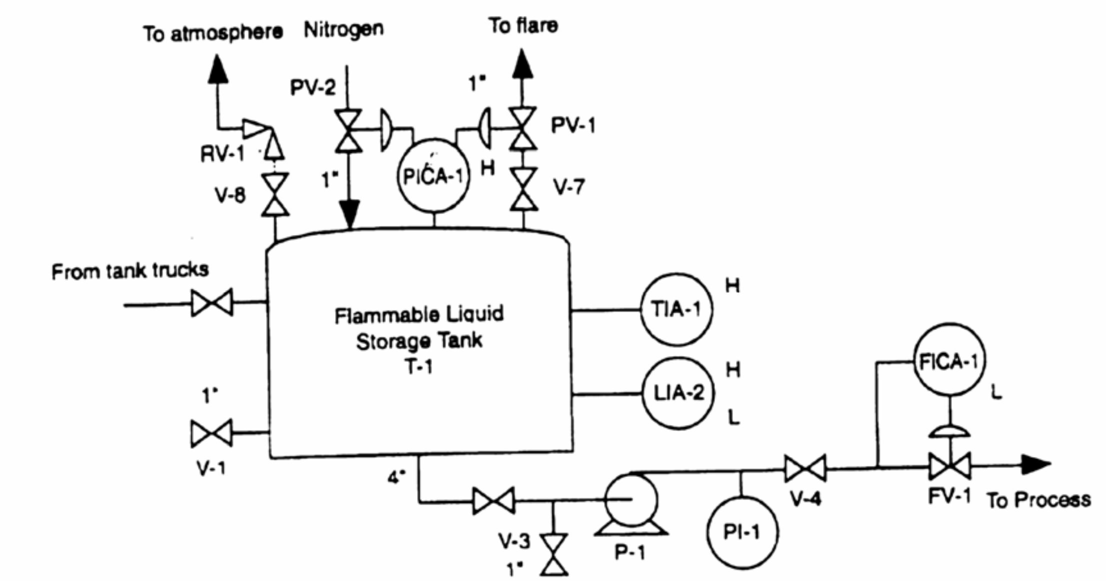

Figure 4-5: P& ID of flammables liquid storage tank (Ozog, 1985)

Each basic event is assigned a probability value. The final probability or frequency of the top event is obtained by combining the probabilities of the basic events. The basic events B_1, B_2, B_3, ….,B_n represents technical failures, human error events and external event causes. The calculations start at the bottom of the tree and proceed upwards to the top event. From this example, the frequency of a major release (3.2 x 10^{-2} per year) is dominated by human errors. Initiating events could be a single or a combination of basic events. For instance, from the fault tree analysis it was found that the following basic events contained human failure elements in them: Basic event B_1: Insufficient Volume in Tank; B_2: Level Alarm fails or ignored; B_3: Wrong Material Fed into Tank; B_4: Truck Tank not sampled before unloading and B_5: Unloading Frequency. The value of top event is the summation of all minimum cut-sets. Basic events B_1, B_2 and B_5 make one minimum cut-set which has a frequency value of 3 x 10^{-2} yr^{-1}. Using Fussell-Vesely (F-V) level of importance this cut-set contribute to 94% of the top event occurrence. It is usually the case that human error dominates a risk assessment, if it is properly considered in the analysis.

Incorporating HRA into QRA has some limitations some of which have been mentioned in section 4.3.1. Most are inherent in the HRA methodologies themselves and in the human error probability data. There exists a large failure rate databank for technical components.

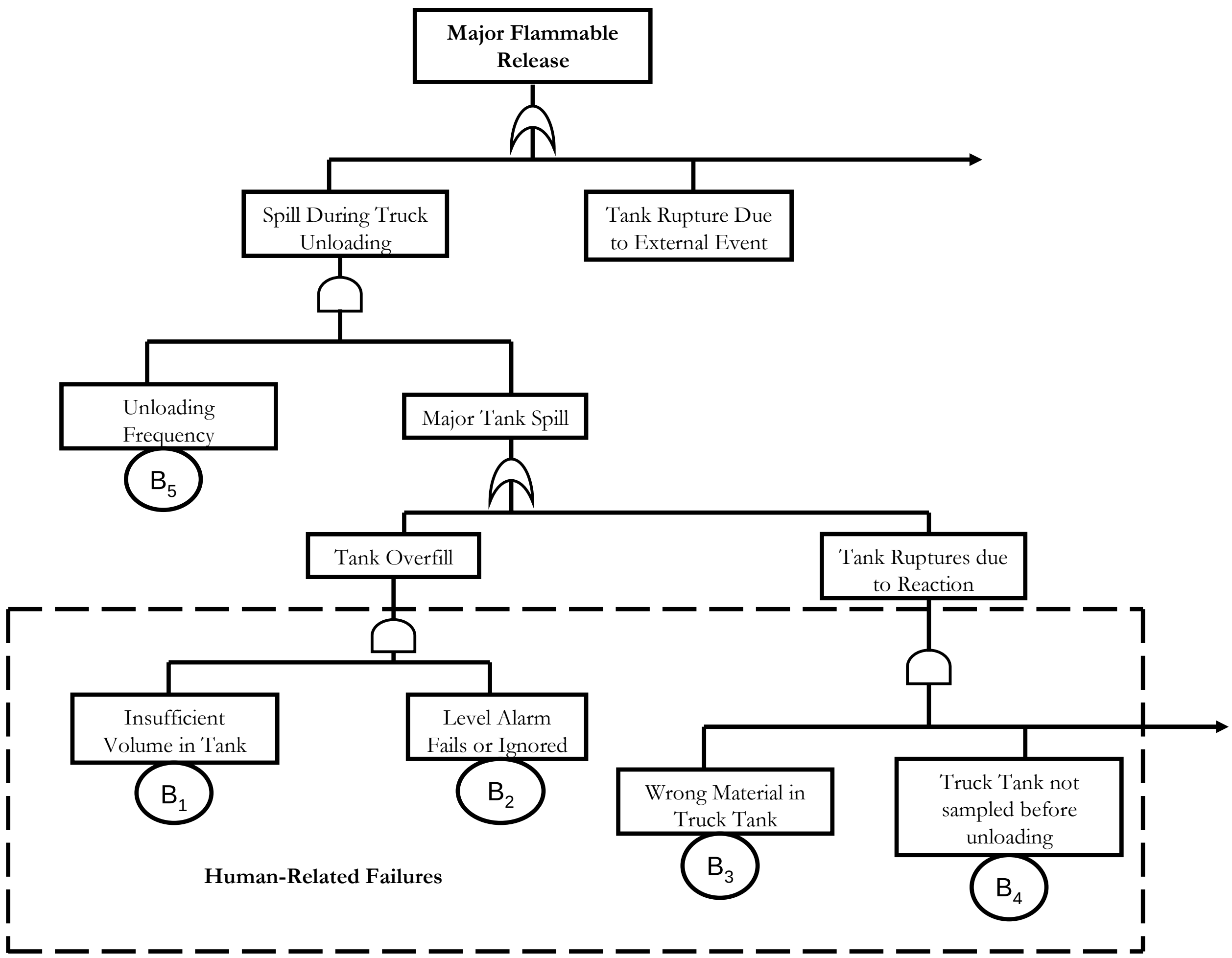

Figure 4-6: Fault tree Analysis of a Major Spill

4.3.5 New Approach

It is also relatively easy to estimate the probability for external events' occurrence. On the contrary, HRA data is rare, outdated and many times purely subjective. However, it is critical that the potential human causes for major accidents be exhaustively identified and quantified for a complete QRA.

Unfortunately, the tools currently used by analysts for hazards identification do not adequately address the problem (AIChE, 1994). HAZOP could have been described as a compromise tool for hazard identification. Yet, it is skewed towards hardware failures. It can be argued that with knowledge and experience one could use it to identify human errors as well. But it is obviously preferable to have a tool to help in error identification even if the analyst does not have much experience and knowledge. Such a systematic method is lacking and this is what this work is striving to achieve.

Moreover, when carrying out a human reliability analysis (HRA), each human error event is assigned a probability of occurrence. The probability value is generic and therefore does not represent the actual conditions of the system or plant being analysed. Each plant conditions differ significantly from others. Analysing and quantifying human factors is to help evaluate the quality of factors affecting operator performance in a particular system or plant. One should be able to establish and measure the EPC/factors that surround each operator error. The intention is that this work shall reflect situation specific factors as far as reasonably practicable, with respect to technical systems as well as human and organisational factors.

The new approach recommends the following:

i) After a fault tree has been constructed, the basic events are qualitatively analysed to find those with human error elements in them.

ii) These are further analysed to find out the specific underlying human factors that could act as error producing conditions.

iii) These human factors are quantified for use in QRA

This procedure is described graphically in fig 4- 4. This approach is divided in two major categories. First is the qualitative evaluation of human factors and then the quantification part.

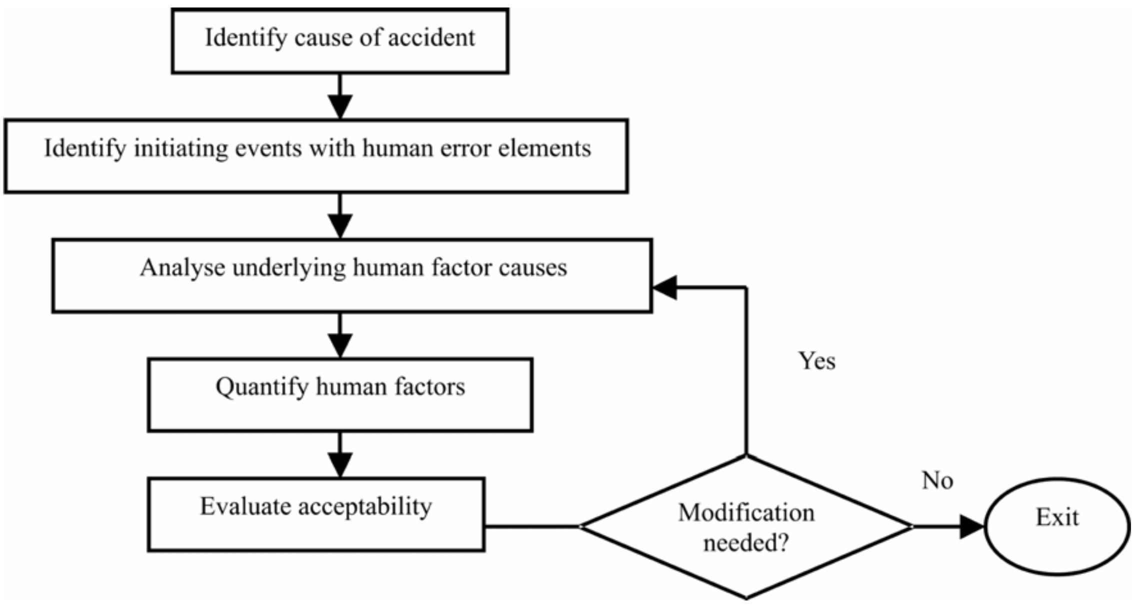

Figure 4-7: Procedure to identify human factors underlying an unwanted event

In broad perspective, the procedure is divided into two parts. The first part is qualitative and will be described in further details in chapter 6. The second is quantitative and will be covered in chapter 7.

5 MATHEMATICAL MODELS

5.1 Introduction

It is clear that most of the factors that affect human performance can only be assessed and solved subjectively. This is because scientific methods have not been adapted well to solve human-related problems, which is partly as a result of lack of data. Objectivity is relative to the knowledge available and if hard data does not exist then cognitive processes have to be used (Saaty and Kearns, 1985). Addressing such a problem requires an approach that enables the use of a variety of relevant information including both "hard" data such as quantifiable information and "soft" data commonly referred to as expert judgement which normally calls for cognitive processes. This approach should facilitate the use of creativity and experiences to structure the complex problem and pursue solutions in a systematic framework.

5.2 Multi-Attribute Decision Analysis (MADA)

The whole human factors spectrums form a complex social-technical problem. It is characterised by a mixture of qualitative units that need to be broken down into more manageable pieces to allow data and judgments to be brought to bear on the pieces, and then reassembling the pieces to present a coherent overall picture to the analyst. The methods of multi-attribute decision analysis (MADA) have been chosen because they are able to transform qualitative input (mostly in natural language) into quantitative output. The qualitative evaluation of human factors will be the input of the analysis. MADA methods apply to problems where the analyst is choosing or ranking a finite number of alternatives which are measured by two or more relevant attributes. (Chen and Hwang, 1992) describe the principle MADA methods.

Two methods are leading in these types of analysis viz Fuzzy sets (Zadeh, 1965) and Analytic Hierarchy Process (AHP). Fuzzy sets are broadly equivalent to the sets found in conventional mathematics and probability theory with one important exception. This exception is that, instead of membership of a set being crisp (that is, an element is either definitely a member of a given set or it is not), set membership is graduated, or fuzzy or imprecise. Set membership is defined by a membership function, $\mu(x)$, taking values between zero and one. Thus a particular issue might be regarded as a member of the set of major social concerns with a membership value of 0.8. A membership function value of 0 conveys definitely not a member of the set, while $\mu = 1$ conveys definitely a member of the set. $\mu = 0.8$ suggests quite a strong degree of belief that the problem is a major one, but not with complete certainty. The reason why fuzzy sets are not considered further is because of the following limitations:

- a lack of convincing arguments that the imprecision captured through fuzzy sets and the mathematical operations that can be carried out on them actually match the real fuzziness of perceptions that humans typically exhibit in relation to the components of decision problems (Chen and Hwang, 1992).
- doubts as to whether prescriptively trying to model imprecision, which is in some sense a descriptive reflection of the failings of unaided human decision processing, is the right way to provide support to deliver better decisions.
- these methods tend to be difficult for non-specialists to understand, do not have clear theoretical foundations from the perspective of modelling decision makers' preferences and have not yet established that they have any critical advantages that are not available in other, more conventional models.

In combination, issues such as these continue to throw substantial doubt on the practical value of fuzzy sets as a practical tool for supporting MADA. They remain for the moment largely confined to the academic literature or to experimental applications, although ideas about MADA based on fuzzy sets have been discussed for more than twenty years (Chen and Hwang, 1992).

AHP was selected for this work because of the following strengths: it is well-known and well-reviewed in the literature; it includes an efficient attribute weighting process of pair-wise comparisons; it incorporates hierarchical descriptions of attributes, which keeps the number of pair-wise comparisons manageable; and most of all, its use is facilitated by available software.

5.3 Analytic Hierarchy Process (AHP)

5.3.1 Introduction

MADA tools are the foundation of this method. These techniques are well-known decision support tools for dealing with complex decision constellations where technological, economical and social aspects have to be covered (Cox et al., 2000). The method was developed by Saaty (Saaty, 1980). It is a means of prioritising impacts through a systematic representation of a problem. It uses hierarchical structure to decompose a problem into attributes and then guide decision makers through a series of pair-wise comparison judgement to express relative strength on impact of the attributes in the hierarchy. These judgements are then translated into numbers.

Analytic Hierarchy Process is a framework characterised by simplicity and at the same time is robust enough to model real world complexities. It is founded on three principles which are important in problem solving. These are the principle of identity and decomposition, the principle of discrimination and comparative judgment and the principle of synthesis of priorities (Saaty and Kearns, 1985).

5.3.2 The Principle of Identity and Decomposition

The principle calls for structuring the hierarchy to capture the elements of a given problem. Structuring the problem hierarchically is guided by no specific rule and therefore allows the user to construct own model, see figure 5-1. This model is known as value tree.

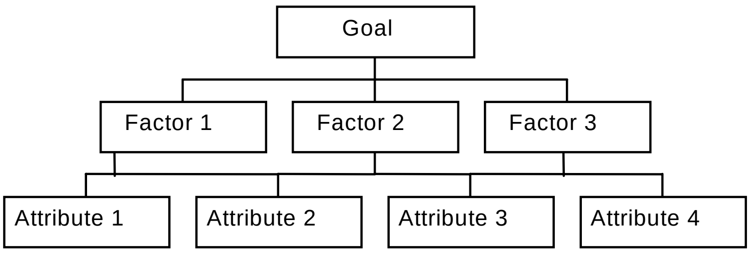

Figure 5-1: Generic hierarchical decomposition

However, an effective way is to proceed downwards with the focus on the top level to criteria bearing on the focus in the second level (factors) followed by sub-criteria (attributes) on the third level and so on. That is from the more general and somewhat uncertain to the more particular and definite. The top most level represents the goal or focus of the problem. The lower levels act as the elements contributing to the levels immediately above (Saaty and Kearns, 1985). The bottom most elements are known as attributes. In the context of this work the overall goal is to determine the quality of human factors index and by assessing those attributes that have direct impact. For the purpose of this work thirty attributes were derived and are outlined on table 6-1 that appears on page 61. They include human factors and safety policy, organisational culture, training, display design just to mention a few. The law of hierarchic continuity requires that the elements of the bottom level of the hierarchy be comparable in pair-wise way according to the elements in the next level and so on to the focus of the hierarchy.

5.3.3 The Principle of Discrimination and Comparative Judgement

Once the problem is decomposed into a hierarchy, each element must be compared to other elements at that same level using matrices of pair-wise comparison. All identified attributes in the same level are compared against each other in a matrix pair-wise comparison to express the relative preference among the factors/attributes on properties that they share in common. The elements in the second level are compared with each other in respect to the overall objective /focus; the third level elements are compared with respect to the appropriate parents in the second and so on down the hierarchy. The questions asked at the bottom level could take the form "When comparing different attributes, which attribute is more important (in achieving the goal)?"

Let η be a finite set of elements. Let φ be a set of attributes (features attached to an object) with respect to which elements in η are compared. When two elements in η are to a criterion in φ then we are performing a binary or a pair-wise comparison. Let $\succ$ be binary relation on η representing "more preferred than" with respect to a criterion in φ. Let $\approx$ represent "indifferent to" with respect to a criterion C in φ.

Hence for any two elements A_i, $A_j \in \eta$, either $A_i \succ A_j$ or $A_j \succ A_i$ or $A_i \approx A_j$ for all $C \in \varphi$. Let ϕ be a set of mappings from η x η to $\Re^+$ (set of positive reals). Let $f: \varphi \to \phi$, and $P_c \in f(C)$ for all $C \in \varphi$. P_c acquires a real positive number to every pair A_i, $A_j \in \eta \text{ x } \eta$.

Example:

A company intends to locate a site in four countries. It compares four countries: A_1 = Germany, A_2 = Kenya, A_3 = Britain and A_4= China using a criterion "Quality and Reliability of Utilities". In this case our elements $A_i = A_1, \ldots, A_4$. Mapping these elements into $\eta \text{ x } \eta$ we have the matrix shown on the next page.

Quality and Reliability of Utilities	A1	A2	A3	A4
A1				
A2				
A3				
A4				

Comparing the elements an analyst came up with the following preferences: $A_1 \succ A_2$, $A_1 \approx A_3$, $A_1 \succ A_4$ and $A_3 \succ A_2$. Implying that A_1 is morepreferred than A_2 and A_1 has the same preference as A_3 given the mentioned criterion.

Let $P_c\ (A_i, A_j) \equiv a_{ij} \in \Re^+$, and $A_i, A_j \in \eta$. For each criterion $C \in \varphi$; $\eta \times \eta$, $\Re^+$ and P_c are mappings of elements to a numerical system.

For all A_i, $A_j \in \eta$ and $C \in \varphi$

$$A_i \succ A_j \text{ if and if only } P_c(A_i, A_j) > 1,$$

$$A_i \approx A_j \text{ if and if only } Pc(Ai, Aj) = 1$$

$A_i \succ A_j$ implies that A_i dominates A_j with respect to $C \in \varphi$. Therefore P_c represents the intensity of preference for one alternative over the other.

And for all A_i, $A_j \in \eta$ and $C \in \varphi$

$$P_c(A_i, A_j) = 1/\ P_c(A_j, A_i)$$

This could be written as $a_{ij} = 1/\ a_{ji} = w_i\ /\ w_j$ and therefore matrix A.

$$A = \begin{pmatrix} a_{11} & a_{12} & a_{13} & a_{14} & \ldots\ldots & a_{1n} \\ a_{21} & a_{22} & a_{23} & a_{24} & \ldots\ldots & a_{2n} \\ a_{31} & a_{32} & a_{33} & a_{34} & \ldots\ldots & a_{3n} \\ a_{41} & a_{42} & a_{43} & a_{44} & \ldots\ldots & a_{4n} \\ . & . & . & . & & . \\ . & . & . & . & & . \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & \ldots\ldots & a_{nn} \end{pmatrix}$$

Let M_1, M_2, ...M_n be any set of n elements and $w_1, w_2, \ldots, w_n$ the corresponding weights or intensities. If we compare each element's intensity with the intensity of every other element in the set with respect to a property that they have in common, then this could be represented as in the matrix shown here below. This type of matrix is known as matrix of pairwise comparison.

$$\left(\begin{array}{c|ccccc}
 & M_1 & M_2 & M_3 & \dots & M_n \\
\hline
M_1 & w_1/w_1 & w_1/w_2 & w_1/w_3 & \dots & w_1/w_n \\
M_2 & w_2/w_1 & w_2/w_2 & w_2/w_3 & \dots & w_2/w_n \\
M_3 & w_3/w_1 & w_3/w_2 & w_3/w_3 & \dots & w_3/w_n \\
. & . & . & . & & . \\
. & . & . & . & & . \\
M_n & w_n/w_1 & w_n/w_2 & w_n/w_3 & \dots & w_n/w_n
\end{array}\right)$$

Where $w_i > 1$, $i = 1, 2, 3, \ldots, n$.

When the intensities w_i are not known then the elements are compared using subjective judgment using a scale of numbers. In such cases there are deviations between the exact measurements and the human judgments and sometimes these deviations are large.

From the matrix, $w_i/w_j = a_{ij}$

For each fixed i, $w_i = 1/n\ (a_{i1}w_1, a_{i2}w_2, \ldots\ldots, a_{in}w_n)$

$$=1/n \sum_{j=1}^{n} a_{ij}\, w_j \qquad (i, j= 1, 2, \ldots, n) \qquad (5.1)$$

This is applicable for consistent matrices, but for cases where there is deviation of a_{ij} we denote n by $\lambda_{\max}$, which is commonly known as the maximum eigenvalue. If A is a matrix of pairwise comparison values aij, in order to find a priority vector, we must find a vector w which satisfies

$$Aw = \lambda_{\max}\, w \qquad (5.2)$$

To solve the particular problem in this work subjective judgment is going to be used because there are no “hard” data available for quantifying different weights of human factors. This approach tries to translate the natural language of factors that are intangible into quantities. An example is; procedures are “slightly more important” than training when it comes to preventing human error.

In the matrix, one begins with an element on the left and asks how much more important it is than an element listed on the top. When compared to itself then the ratio is 1. The reciprocal is entered in the transpose position of the matrix and therefore we only deal with n(n-1)/2 judgments where n is the rank of the matrix.

A scale to make subjective pair-wise comparisons is recommended (Saaty, 1980; Saaty and Kearns, 1985) and is illustrated in table 5-1. The basis of this scale and justification of why it is indeed more preferable than all others can be found in (Saaty, 1980). Judgment is elicited from people who have knowledge about the relative importance of elements with respect to the overall problem. In this study a questionnaire was formulated and respondents were people from the process industry who are directly or indirectly involved with EH & S departments. The results of the questionnaire will be discussed in chapter 6. In making the comparisons of X with Y questions like "which is more important or has more impact" are asked. If the elements on the left are more important than the element on the top then a positive integer ($1 < w < 9$) is entered. If it is less then the reciprocal of the integer will be entered. The relative importance of any element to itself is one and therefore the diagonal of the matrix (upper left to lower right) contains 1.

Table 5-1: Scale for comparisons (Saaty and Kearns, 1985)

Intensity of Relative Importance	**Definition**	**Explanation**
1	Equal importance.	Two activities contribute equally to the objective.
3	Moderate importance of one over another.	Experience and judgment slightly favour one activity over another.
5	Essential or strong importance.	Experience or judgment strongly favours one activity over another.
7	Demonstrated importance.	An activity is strongly favoured and its dominance is demonstrated in practice.
9	Extreme importance.	The evidence favouring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between the two adjacent judgments.	When compromise is needed.

Since small changes a_{ij} brings about small changes in λ_{max}. This is the deviation of the maximum eigenvalue from n and this is defined as the consistency measure and is known as consistency index, CI. It enables the evaluation of closeness of derived scale from and underlying scale which we wish to estimate. Therefore,

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{5.3}$$

A randomly generated reciprocal matrix from the scale 1 – 9 is known as random consistency index (RI). It is obtained from large number of simulation runs and is dependent on the order of the matrix n. Saaty generated an average RI for matrices of order 1 to 10 using a sample size of 500 (Saaty, 2000) and this is shown on Table 5-2.

Table 5-2: Values for Random consistency Index

Size of Matrix, n	1	2	3	4	5	6	7	8	9	10
Random Consistency Index, RI	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

The consistency ratio CR was defined as the ratio of the consistency index CI to an average RI for the same order matrix, therefore

$$CR = CI/RI \tag{5.4}$$

A consistency ratio (CR) of 0.1 or less is considered acceptable.

6 DEVELOPMENT OF QUALITATIVE HUMAN FACTORS TOOL

6.1 Introduction

The human performance can best be presented using human behaviour models. Models that deal with cognition are discussed in a number of behavioural sources (Norman, 1988; Wickens and Hollands, 2000). Most of the HRA use stimulus-response models and in this case much of cognition is not considered. On the contrary, human beings should be considered as information processing systems which include perception and perceptual elements, memory, sensory storage, working memory, long term memory and decision making (Sanders and McCormick, 1993).

The model adapted for this work combines the elements of stimulus-response and the information processing domains. This will help consider the aspects of detection, recognition, discrimination and interpretation.

A human machine system comprises of a human operator, a control and a display/alarm, see fig 6-1. Reliability of the control and that of the display/alarm is easy to obtain using the existing reliability methods.

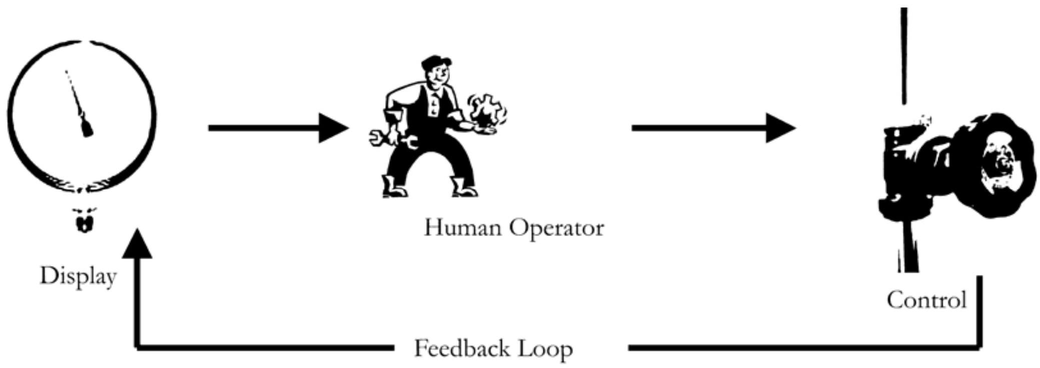

Figure 6-1: Basic components of human system interface

This set-up is common in offloading operations. The operator observes the level gauge and closes the valve when the tank is full. The illustrative example demonstrates an operation that is entirely manual. For such an operation and any other operator task the main steps that take place are illustrated in fig 6-2. It is observable that in this model detailed information processing has been included.

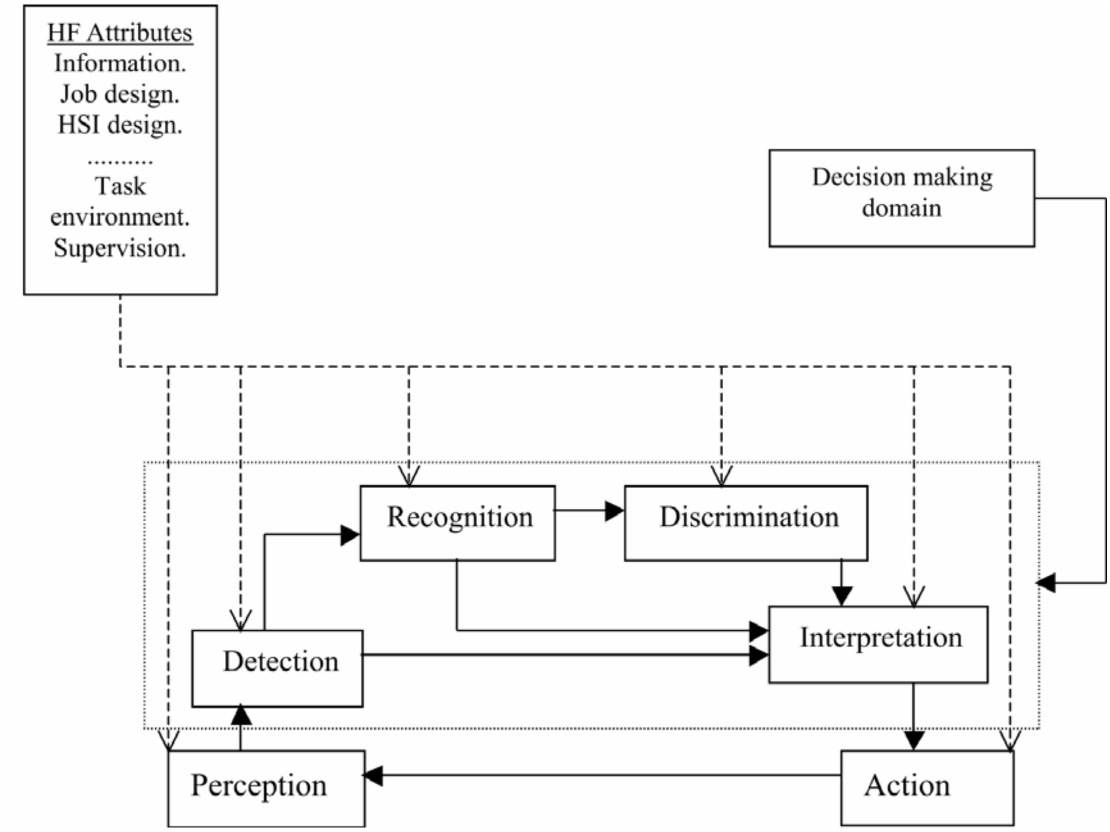

Figure 6-2: Steps in a human operator control operation: adapted from (Kariuki and Löwe, 2006; Wickens and Hollands, 2000)

There are three main perceptual categories viz. detection, recognition and discrimination. These are defined as follows (Snyder, 1973):

Detection: This is when an observer correctly indicates his decision that an object of interest exists in the field of view.

Recognition: When the observer correctly indicates to which class of objects the detected object belongs.

Discrimination: When the observer correctly separates the single target of interest from the group of recognised targets

The quality of these three categories brings a clear situation awareness and therefore makes the operator be able to interpret and act correctly in a given situation. An operator error can occur at any of these steps. During perception phase the operator can, for example, misread information, misperceive or fail to detect visual or auditory information. He may fail to make the right decision due to memory capacity overload, similarity of information perceived or due to lack of or incorrect knowledge. Wrong action could be contributed by similarities in (hard to discriminate) controls or interruption from the environment among others (Kariuki and Löwe, 2006).

As illustrated in fig 6-3, to a big percentage the output operator errors are determined by the quality of several system/plant attributes $x_1, x_2, \ldots\ldots x_n$, on the left hand side of the diagram. The attributes are characterised by the performance measures $r_1, r_2, \ldots, r_n$. These attributes are human factors. Since each human factor attribute influences the error causation differently then weights $\omega_1, \omega_2, \ldots\ldots \omega_n$ are assigned (Kariuki and Löwe, 2005; Kariuki and Löwe, 2006). The procedure to assign r and ω is discussed in later sections.

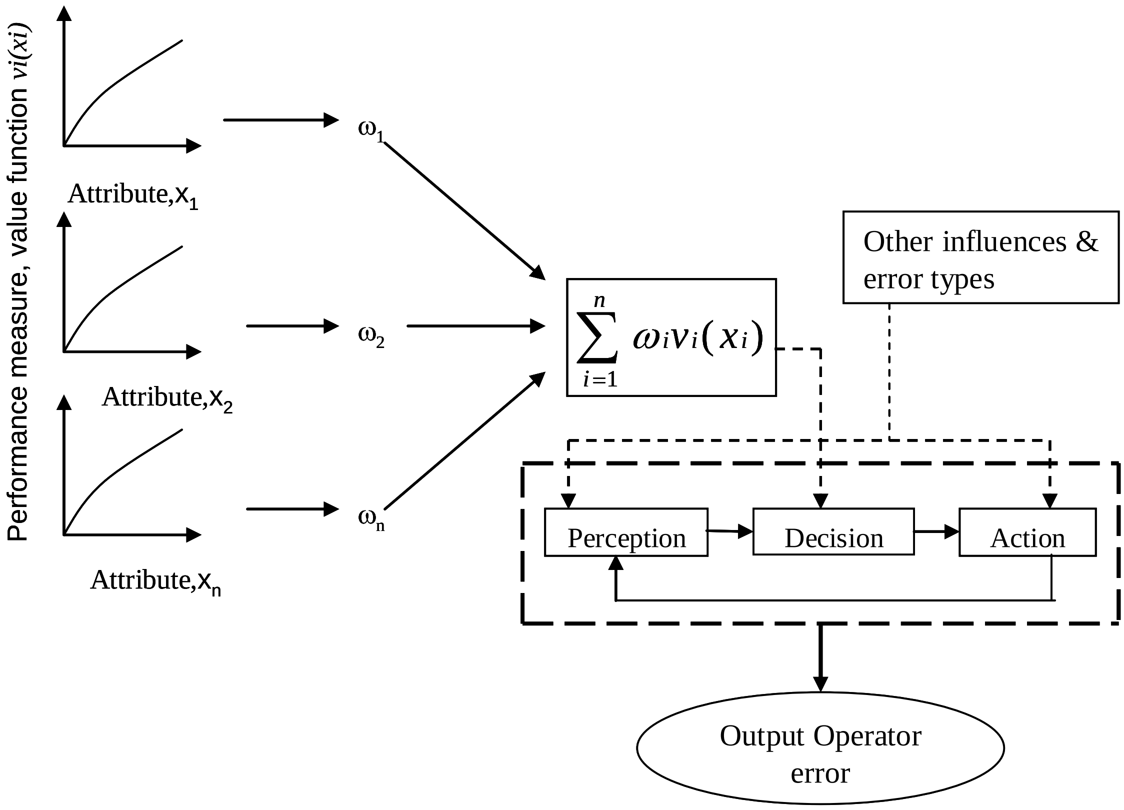

Figure 6-3: Factors influencing frontline operator error

Not all errors are caused by inadequate human factors. Others could be deliberate acts of sabotage and single extraneous acts and are classified under "other influences and error types". These are not discussed further in this work.

In order to increase operator reliability the performance measures, r_i for attributes that have influence on perception, decision or action of the operator should be maximised. That means maximising $r_1, r_2, \ldots, r_n$ in order to reduce error opportunities.

It was mentioned in section 5.3.2 that this work has a total of thirty HF attributes. In the next section all the steps that were undertaken to develop and classify these attributes will be discussed. The development of HF guideline builds the foundation of this task. The current state of HF in the process industry and development of the actual HF guideline are described. This consequently leads to the classification of HF attributes.

6.2 Development of Process Industry Management (PRISM) Guideline

6.2.1 Background

The European Union chemical process industry realised the importance of human factors in relation to safety. For this reason European Process Safety Centre (EPSC) formed a network called Process Industry Safety Management (PRISM). It was comprised of leading operating companies, consultancies and research institutes in Europe. PRISM was founded with the aim of finding ways to improve safety in the European process industries through raising awareness of, and sharing experience in, the application of human factors approaches. In addition the network aimed to stimulate the development and improvement of human factor approaches in order to address industry-relevant problems in batch and continuous process industries (PRISM, 2004). This network focused on small and medium enterprises (SME's) and big firms that do not have mature safety management systems. The overall aims of the project were improvement of safety in process industries through:

- Sharing best practice on Human Factors.
- Bringing together the best from Industry /Authorities/Universities /Consultants.
- Identifying unmet industry needs.

The network had four focus groups, structured in such a way that all the human factor areas were sufficiently covered. The groups were as follows:

- ✓ FG1: Cultural and organisational factors
- ✓ FG2: Optimising human performance
- ✓ FG3: Human factors in high demand situations
- ✓ FG4: Human factors as part of the engineering design process

The final deliverable for each focus group was a HF guideline on the respective areas. Focus Group 4 of the network was composed of a team from TU Berlin (including the author), ExxonMobil and a representative from Snamprogetti. Before the guidelines were developed TU-Berlin investigated human factors state-of-the-art in the European Union chemical process industry.

6.2.2 State-of-the-art in the process industry

6.2.2.1 Internet-based survey

A large-scale internet-based survey across Europe was carried out. More than 70 representatives of small, medium and large enterprises were requested by email, telephone and/or in person to fill out a questionnaire.

An internet based questionnaire was created because it possessed the following advantages:

- its assured that the questionnaire is anonymous
- no macros are required as in case of excel case
- good and simple distribution to "users" is established
- the questionnaire follows a systematic approach
- the "user" is guided through the questionnaire
- generally, the aim is to avoid that any questions are left unanswered
- the questionnaire provides multiple choice wherever appropriate
- statistical evaluation of large data amounts can be fully automated

The questionnaire was installed on the internet and tested for compatibility with different hardware and software systems (Löwe et al., 2005).

6.2.2.2 Results

Some of the numerous analyses and interpretations of the survey that were made are presented as follows:

What are the percentages of the operating states when events occur?

The results are illustrated on the figure 6-5 (Löwe et al., 2005). There is a clear indication that most events take place when the human operator interacts with the system. Loading/unloading, maintenance/repair and start-up/shutdown operations constitute 52% of these events and coincidentally that is where the biggest interaction between the operator and the system is found. For comparison the results of a study performed by Uth, who examined events in Germany in the period from 1993-96 are presented. Conspicuous is, that in 50% of the events occurs in normal operation procedures. Loading/unloading procedures were not considered separately. Loading/unloading operations are part of the *normal operation* of the plant. Adding the events during loading-unloading procedures to the events during normal process operation yields a result that agrees very well with the percentage of the Uth study (Uth, 1999).

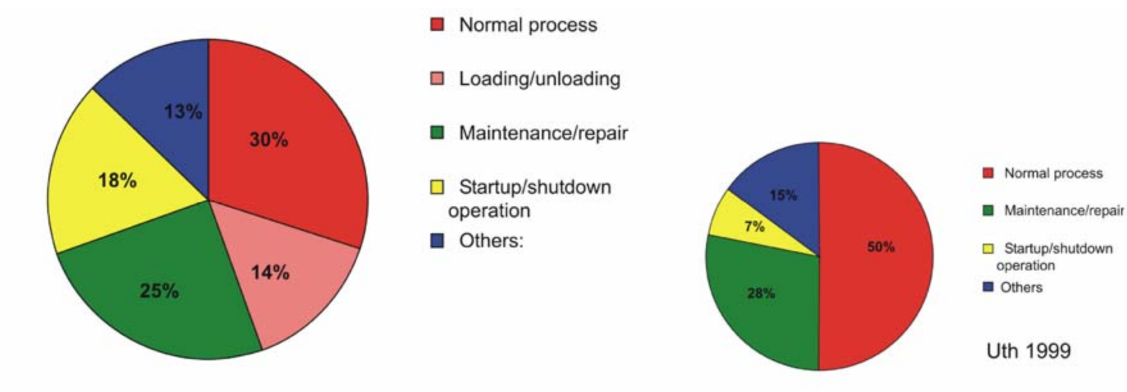

Figure 6-4: Operating state when events occur

"The causes of the events are:"

Only 23% of the events are attributed to technical failures. The respondents felt that 64 % of events are due to human failures.

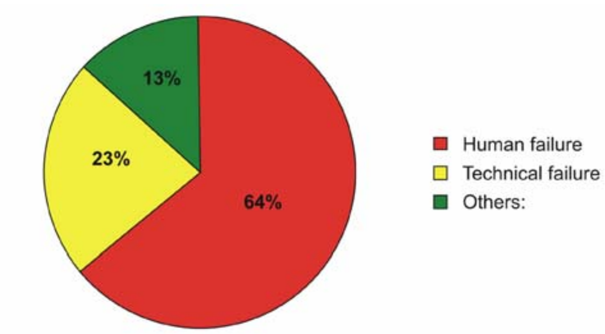

Figure 6-5: Major causes of events in the process industries

The causes given under "others" were examined for a comparison with the study carried out by (McCafferty, 1995). McCafferty examined the events in the USA in oil and gas companies. In his study 80% are caused by human failures. Some causes of events named under "others" are: Work places, management system (which was mentioned more than once), systems failure, design, lack of knowledge of chemistry. Some of the causes like 'inadequate work places' and 'inadequate management system' are considered to be in the area of human failure. Adding these to human failure causes corresponds to the statistics obtained by McCafferty.

The causes of the human failures are?

Of all the human failures 59% are attributed to organisational failure and 25% are due to inadequate facilities. These may be termed as inadequate technical design of the plant

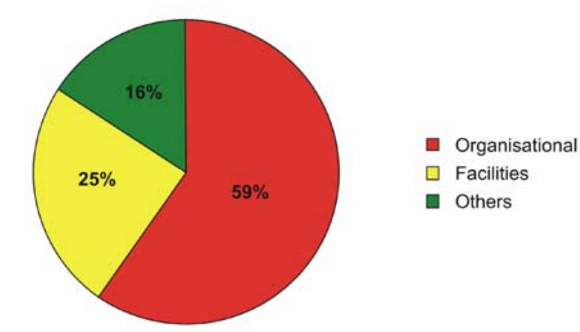

Figure 6-6: Causes of human failures

In summary, the study came out with the following conclusions, which are relevant to this work:

- ◊ A large number of companies do not have experts on HF / ergonomics.
- ◊ Causes of unwanted events are predominantly human failures.
- ◊ There exists none or rather no systematic methods for considering HF in the design process

It could be said that human factors have not yet been given the importance they deserve in order to reduce human failure in the industry. These results could be attributed to the following (Baybutt, 1996):

- Lack of awareness: engineers pay much attention to machine reliability and fail to factor-in the end user.
- Lack of need: many engineers are still unaware of the benefits that considering human factors might bring.
- Misunderstanding of human factors: some engineers might think that it is some psychological study by which they are going to be judged rather than improve the safety in the plant.
- Fear of the effort of involving human factors into the plant design: engineers normally have already a big workload and might fear that including farther human factor studies might overload their capacities.
- Fear of the companies that by starting to consider the human factors, the resulting guidelines and recommendations will end being obligatory and of expensive implementation.
- Lack of integration: even if some approaches are already available, they have not been implemented yet into the industries, partially because redesigning an already working plant is difficult and expensive and on the other side because the effort of having human error analysts, behavioural scientists and human factor specialists working together has not been done yet.
- Lack of approaches to solve some human factor issues, especially when they involve organisational or socio-technical problems.
- Lack of qualified analysts: due to the novelty of this science there are not enough experts with an adequate knowledge on the fields of chemical engineering, risk assessment methods, human error analysis and human factors engineering.
- Lack of motivation: until 1990 there were no regulations or directives that forced consideration of the human factors.

6.2.3 The PRISM Guideline

The aim of the guideline is to assist engineers to design a process facility that addresses the capabilities and limitations of the operator. It shall be applicable to small and medium enterprises as well as large process industry set-ups. The guideline was written to act as a one-step source of information of human factors requirements in all engineering design. Both engineers with human factors background as well as those with no practical experience in this field could use it. The guideline covers the five main areas that are represented in figure 6-8.

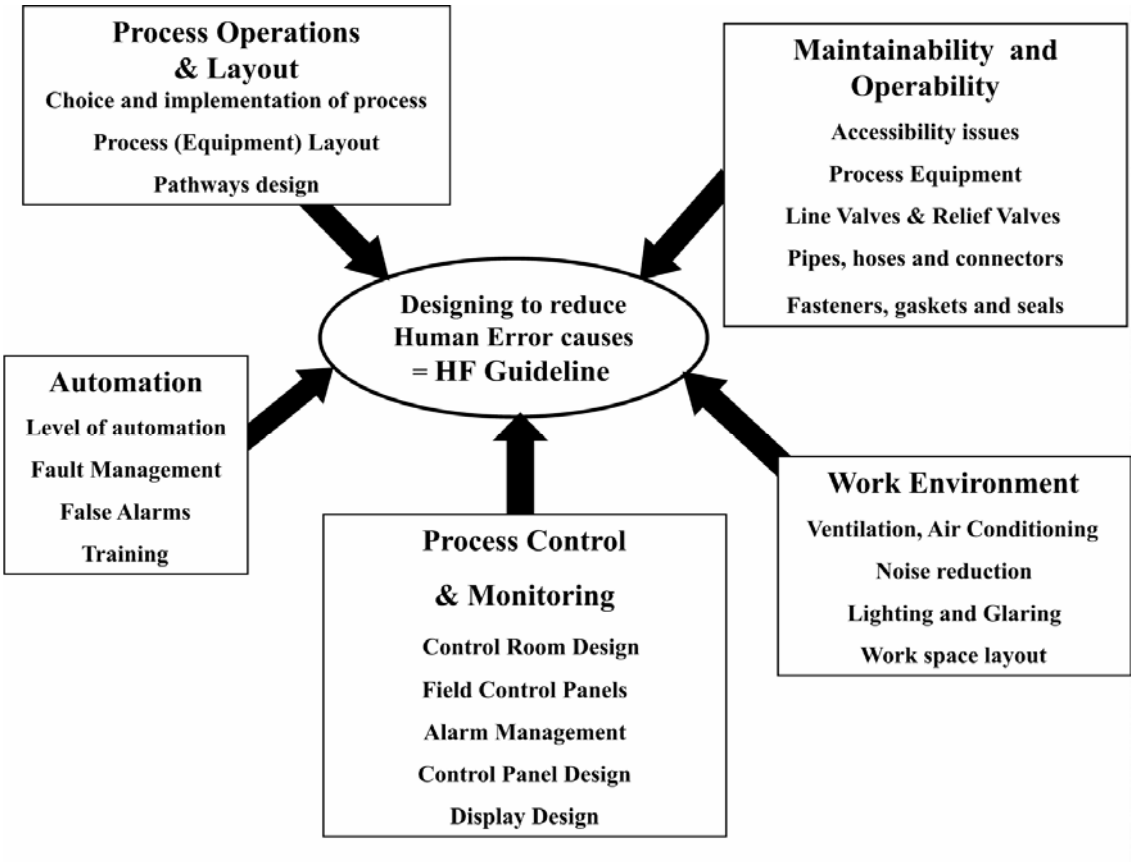

Figure 6-7: Subject areas for consideration of Human Factors during design (Kariuki and Löwe, 2005; Löwe et al., 2005)

For effective practical application the guideline is provided with helpful tools, diagrams and graphics. The guideline is published on the PRISM- Homepage (PRISM, 2004). It is easy to read and use because it has a lot of cross-references to other human factors resources that are relevant.

6.2.3.1 Practical experience

To ensure practical applicability a validation of the guideline was carried out (Löwe et al., 2005). This validation was done at Chinoin Co. Ltd, member of Sanofi-Aventis Group. This plant is located in Budapest, Hungary.

The validation was aimed at answering the following questions:

- Is the guideline applicable in the practical world?
- Does it cover the most important human factors issues?
- Is it understandable by both human factor experts and non-experts?
- Does it serve as an eye opener to the wider human factors field?

There was an agreement that it was a good idea to come up with the guideline. This is because the process industry still lacked a single source of human factor guidance. The little that is available is incomplete and is scattered in the general safety regulations and standards. To bring them together will only mean additional pressures to cost and time resources allocated to the design activity.

Chinoin Co. Ltd as many other companies is outsourcing most of its engineering work. This is of course economical but comes with major challenges. The contractors sometimes have a standard design that is not completely tailored to fit the operating needs of the customer.

One of the major projects currently being undertaken is the reduction and reconfiguration of alarms. The design of this distributed control system (DCS) is based on international standardisation. On a particular day, for instance, 18% of the alarms appeared as critical, 80% as warning and 2% as advisory. It had already been found out that most of the alarms that appear as warning and critical are actually nuisance alarms. An example is the level alarm for nitrogen that does not require any operator intervention or a warning in appearing due to delayed signal response. In the guideline it is suggested that on the higher side the critical alarms should be 15% while warning and advisory should be 45% and 55% respectively.

In the same guideline the following is a suggested criterion for prioritising alarms:

Priority 1: The abnormal situation may result in major consequences. The operator must act immediately. (Emergency action or Critical)

Priority 2: An abnormal situation may bring major process upset but the operator still has some time to act. (Warning or caution)

Priority 3: The existence of abnormal situation has no immediate effect on the process and calls for the operator to monitor the situation. (Monitoring, informative or advisory).

Should the human factor design guideline have been available during the design it could have assisted in pinpointing the most important areas in alarms design and management and therefore too much effort would not be effected to carry out this modification.

PRISM Guideline was seen to be a good basis and a source of information for engineers on the issues to do with human factors during design. To make more complete it was felt that more cross-references are needed in areas where specific guidelines are available.

6.3 Classification of Human Factors

Human and organisational factors that are known to have influence on the performance of the operator are put in various groups. One of the most challenging tasks was to reach a consensus on the most practical classification of the whole human factors domain. The whole spectrum is large and has been approached in different ways by different authors (Attwood et al., 2004; Löwe et al., 2005). Moreover, factors that may apply in other industries e.g. nuclear, medical and/ or aviation may not be applicable in the chemical process industry. The classification of human factors was achieved through a wide consultation with the petro-chemical and chemical process industry. This was initially done during the development of PRISM guidelines mentioned in the earlier section and is illustrated in table 6-1.

This classification has been validated twice. The first validation took place at Chinoin Co. Ltd as a part of PRISM guidelines validation as mentioned earlier.

The second phase took place as part of a validation of a software to assess quality of human factors in the process industry. This was done at Bayer CropScience in their Frankfurt site. In this exercise it was agreed that the classification covered most of the factors that could affect human operator performance. But it was found that some attributes like “HF policy” need to be elaborated. In summary the factors outlined in table 6-1 are thought to have the biggest influence on the operator performance. If any of them is inadequate then there is a higher probability of human error event.

Table 6-1: human and organisational factors in a process plant (Kariuki and Löwe, 2006)

Factors	Attributes
Organisation (ORG):	A1 Human factors and safety policy A2 Organisational culture A3 Management of change A4 Organisational learning (audit & reviews) A5 Line management & supervision
Information (INF):	B1 Training B2 Procedures & procedure development B3 Communication B4 Labels & signs B5 Documentation
Job Design (JD):	C1 Staffing, work schedules C2 Shifts & overtime C3 Manual handling
Human System Interface (HSI)	D1 Design of controls D2 Displays D3 Field control panels D4 Tools (hand) D5 Equipment & valves
Task Environment (TE):	E1 Lighting /Illumination E2 Temperatures E3 Noise E4 Vibration E5 Toxicity
Workplace Design (WD):	F1 Facility layout F2 Workstation configuration F3 Control room F4 Accessibility
Operator Characteristics (OP):	G1 Attention/ motivation G2 Fitness for duty G3 Skills and knowledge

In the section below, these factors are elaborated further. The qualitative evaluation is done on a five level scale; from poor as the lowest to excellent as the highest. The factors are introduced here but the levels of maturity are listed on appendix A (Vadillo, 2006).

6.3.1 Organisation

6.3.1.1 Human factors policy

An adequate policy is the driving force for improving and implementing an organisation's human factors management system so that the organisation can maintain and potentially improve its human factor performance. By defining a human factor policy the organisation is recognising the need to consider the role of the human in operating or maintaining equipment or facilities or the impact of the equipment on the operators and maintainers. This policy should therefore reflect the commitment of top management, which consists of a person or group of people who direct and control an organisation at the highest level, to comply with applicable legal requirements and other requirements, to prevent accidents and to continually improve.

6.3.1.2 Organisational and Safety Culture

This factor is a major component in determining an organisation's safety performance and behaviour. Many researchers have worked on this field and therefore there are different ways of understanding and defining safety culture. Organisational culture is "a pattern of basic assumptions-invented, discovered, or developed by a given group as it learns to cope with its problems of external adaptation and internal integration- that has worked well enough to be considered valid and therefore, to be taught to new members as the correct way to perceive, think and feel in relation to those problems" (Schein, 1985). Baldrige National Quality Program (BNQP, 2005) divides safety culture in four different stages:

a. Fire fighter: at this level problems are solved only when they have already appeared. The origins of the problems are not analysed.
b. Compliance driven: at this level only the minimum legal requirements are achieved.
c. Risk management: at this level a systematic method is developed for identifying and controlling hazards. Safety tasks and responsibilities are communicated.
d. Continuous improvement: this level includes the risk management level and additionally safety incentives are used, improvement is encouraged through motivation and leadership.

6.3.1.3 Management of change

If the change is not well analysed, planned, implemented and controlled it can turn out to be reducing the defences against major hazards. "Companies should assess the workload and other implications of restructuring to ensure that key personnel have adequate resources, including time and cover, to discharge their responsibilities." (HSE, 2003)
Organisational changes include changes in role and responsibilities, organisational structure, staffing levels, staff disposition and others that might directly or indirectly affect the control hazards, such as changes in reporting relationships, objectives, resources, management system, available expertise for design, engineering support, procurement, etc.
A change process should include getting organised for the change, assessing its risks and implementing and monitoring the change.

6.3.1.4 Organisational learning (audit and reviews)

An audit evaluates whether the state of HF conforms to planned arrangements including the legal requirements and whether it has been properly implemented and is maintained. Internal audits of human factors aspects can be performed by personnel from within the organisation or by external persons selected by the organisation, working on its behalf. In either case, the persons conducting the audit should be competent and in a position to do so impartially and objectively. In smaller organisations, auditor independence can be demonstrated by an auditor being free from responsibility of the activity being audited (McLeod, 2004).

6.3.1.5 Line management and supervision

Supervision is a critical management function with great influence on health and safety issues, even if it is not always recognised as the direct cause of an accident in incident reports. It is important to determine which supervisory factors or characteristics are especially significant to health and safety issues.

6.3.2 Information

The main challenge is to ensure that operators have all the information they need to carry out their tasks safely and efficiently. Operators can receive information about the plant through direct perception, communication with the others and through displays and alarms. Operators must also know how to act according to the state of the plant.

6.3.2.1 Training

Training is a factor that provides the worker with the knowledge and skills required to be able to cope with tasks especially those that are novel or unique. New workers or changes in the control panel design, equipment design, job aids, procedures, new team or organisational structure might require additional training. Training is a key to improving human performance but should not be used to compensate for inadequate procedure design, labelling of equipment and poor HIS design. Common problems with training could be associated with inadequate training design, for instance classroom lectures with no practical exercises; training not adequately managed and monitored e.g. operator miss out training and therefore does not master the skills. Evaluation to see how successful the training has been is not carried out.

6.3.2.2 Procedures and procedure development

The aim of procedures is to reduce the amount of decision-making required and the need for human memory to retain every single step and references of the task being carried out. Common problems encountered include incomplete procedures on assumption that an operator could complete the task using common sense or procedure steps are presented in the wrong sequence. Others could be wrong procedure used on equipment. This could be caused by wrong labelling, wrong procedures included in a work package or changes in an equipment are not indicated on the procedure. If the procedures are inadequate or problematic, they should be investigated in order to determine the level of maturity.

6.3.2.3 Communication

Lack of proper communication is detrimental to safety and has caused a number of accidents e.g. the Piper Alpha disaster. A good and effective communication allows the process to work properly and it has to be carefully implemented considering reporting lines, information exchange, employee involvement, two-way communication, etc. Communication has to be managed, which means that all channels of communication within an organisation and between organisations have to be systematically planned, implemented, monitored and revised.

6.3.2.4 Labels and signs

Labels and signs are important features for safety, because they remind the operator of the identity of equipment and key information. Labels identify plant equipment, components or areas. Signs contain messages that inform about hazards or remind about protective equipment requirements, instructions or some important procedures. Some of the problems found with labels are unclear and ambiguous language that include long messages, inadequate layout which make them invisible.

6.3.2.5 Documentation

Documentation includes user guides and manuals, user handbooks and technical instructions, job performance aids, quick reference guides, and instruction placards. It contributes to the user's cognitive understanding of the hardware, software, and human interactions with these other components of the system. Therefore, having the right documentation can improve performance in operation and allow a better communication and training, a better maintenance and revision with a lower risk of ambiguity and deviations.

6.3.3 Job Design

Job design is the specification of the contents, method and relationships of jobs to satisfy technological and organisational requirements as well as the personal needs of job holders. While defining tasks, the workers abilities and limitations must be taken into account in order to achieve the best possible human performance. In order to achieve this goal it is important to ensure an adequate number of qualified staff, with well planned shifts and work schedules in order to reduce fatigue, stress and loss of concentration as much as possible. The job should also be designed in such a way that risks to worker health and safety are as low as possible especially for manual handling tasks.

6.3.3.1 Staffing

An adequately staffed organisation ensures that personnel are available with the proper qualifications for both planned and foreseeable unplanned activities. Staffing is a dynamic process in which plant management monitors personnel performance to ensure that overall organizational performance goals are met or exceeded. The result of an effective staffing process is a balance between personnel costs and the achievement of broader organisational goals. Some of the problems related to staffing would be:

- Qualified staff being too few on a shift or a particular job that requires skilled workers.
- Insufficient personnel leading to overloading and therefore stress.
- Excessive personnel leading to poor co-ordination and communication.

6.3.3.2 Work schedules, shifts and overtime

Work schedules, shifts and overtime can have an impact on the way in which work is carried out. Human body has a biological rhythm within which the values of different physical measurements (such as body temperature, heart rate, and blood pressure) change. According to the stage of the rhythm in which the body is in, human alertness and performance can be altered. Statistics on accident and the time at which these accidents occur show that for each accident in the morning shift, there are 1.15 accidents in the evening shift (4pm until midnight) and 1.2 accidents in the night shift (midnight until 8am) (Attwood et al., 2004). This biological rhythm is important in designing of job and shifts.

While planning and designing work schedules, breaks and shifts, work rate and energy expenditure required for different tasks and efforts must be considered in order to plan the different duration and levels of work, rest periods, fatigue and posture effects. U.S. Defence Standard (DOD, 1997) provides guidance on this issue.

6.3.3.3 Manual handling

When manual handling is not safely performed, worker health can be damaged resulting in musculoskeletal disorders (Attwood et al., 2004). A qualitative screening approach assists in selecting the physical work tasks that need further consideration, because their risk needs to be reduced. Musculoskeletal disorders can be cumulative trauma disorders (CTD) due to repeated exposure to physical activity or an acute trauma caused by for instance a fall.

6.3.4 Human System Interface

This is the main point of interaction between the human and the system. Through this interface the operator knows what is going on in the system and can give some input, feedback or controlling measures to the system that in the end will alter its status. The limiting factor in this interface depends on the sensory, perceptual and physical operator's capabilities (FAA, 2004).

6.3.4.1 Design of controls

There are different types of controls and they should be designed and chosen according to the accuracy and speed of operation required, to the available surface for its installation, to the operators' expectations on how to operate them and to the consistency with other controls in the plant with the same function. The PRISM Guideline is a very valuable document for this aim.

Inadequate design of controls could be, for example, designing too small controls that can accidentally be activated while switching on or off other controls. Another example is the consistency of the controls, at least in the same plant. If by activating some controls clockwise the flow increases and in some other cases it decreases, it will lead to errors especially during emergency situations.

6.3.4.2 Displays

This includes both audio (alarms) and visual displays. Displays should provide the operator with a situation awareness of the process, so that the he/ she can then take the right actions and decisions at the right time. The amount and quality of the information has a direct influence on the identification, detection and reaction time needed by the operator. (PRISM, 2004) and (FAA, 2004) provide with very valuable information on displays. Inadequate design could be inaccessibility from normal working condition or too much unnecessary information.

6.3.4.3 Field control panels

These are the panels that contain displays and controls to monitor and control the operation of process equipment in a local area of the plant. It is very important that these fields are accurate and complete in labels, signs and instructions as well as easily and clearly visible with a good arrangement of the controls and the displays on the field and with all the lights and indicators working and connected to the right equipment .

6.3.4.4 Tools

Tools must be designed in such a way that they allow operators perform the task in the safest possible way. The size and morphology of the tool should fit the different users and foresee the possibility of being used by right- or left-hand sided people. The required tools should be available in the required amount at the workplace in order to prevent workers from performing the task without support of the adequate tool or substituting the tool by some other object not designed for this function.

6.3.4.5 Equipment and valves

Compressors, pumps, reactors, centrifuges, filters, furnaces, heaters, loading and unloading racks, columns, tanks and vessels fall under this category. Each of them should fulfil some guidelines to achieve the best practice (see PRISM Guidelines). Adequate accessibility to the equipment, to its different components and its local operation and emergency controls and displays, which will be showing the actual status of the important variables and parameters, will make the design of the plant and equipment approach the best practice. The location of the equipment, the safety showers, labels, procedures and warnings must also be taken into account. Ventilation, sample points, purges and maintenance and cleaning of the equipment must also be studied and integrated to the design.

When designing and installing valves, factors such as accessibility, priority and functionality arrangement and the force and position in which it has to be executed must be studied and considered.

6.3.5 Environmental factors

Environmental conditions that can affect performance include excessive vibration and noise, temperature extremes and insufficient lighting. These adverse environmental conditions can stress personnel, interfere with performance and increase the likelihood that they will commit errors while performing a task. Work conditions that require protective gear, such as confined space environments, or that require unusual physical postures, also can interfere with task performance, as may poor housekeeping.

6.3.5.1 Lighting / Illumination

Adequate lighting is required for accurate performance of nearly every task in a process plant. The amount of light falling on a surface depends on the light source, its distance from the surface, the angle of the surface to the light source and the number of light sources and reflecting sources in the immediate environment (Attwood et al., 2004). This affects visibility.

The ability to accurately perceive colours is affected by lighting. Very low lighting levels also adversely affect colour discrimination. Glare and flicker will also reduce visual performance. Glare occurs when the luminance (the perceived brightness of an object) level is annoying. It may reduce contrast, interfere with reading and inspection tasks and cause visual fatigue. Flicker causes discomfort and eye fatigue when reading.

6.3.5.2 Temperature, humidity and wind chill

Humans can adapt to big variations in external temperature, but the body's temperature is within a narrow range (36.1-37°C) and even small changes out of this range of internal temperature can produce serious damage to health and human performance. When workers begin to experience heat stress, they may become confused and disoriented, in addition to experiencing physical symptoms, and are very likely to commit errors if they attempt to continue working. Exposure to cold affects the performance of manual tasks. Decrease in the ability to control hand movements begins at an air temperature of approximately 12° C. The impact of environmental temperature on the human is also dependant on humidity and ventilation at the workplace.

6.3.5.3 Noise

Noise an auditory stimulus that does not provide any additional information to the task that is actually being performed or completed. It ca disrupt communications, affect the ability to perform tasks and annoy personnel. Noise over 90 dBA affects the overall performance. Over 100 dBA it affects the monitoring performance over a long duration. Task with long short-memory component, complex tasks and tasks requiring high perceptual or information processing capacity or performed without pauses between responses are affected by noise. However noise does not reduce performance on simple routine tasks or motor performance.

6.3.5.4 Vibration

There are two types of vibration that may cause errors. The first is whole-body vibration, in which vibration is transferred to the worker from standing or sitting on a vibrating surface. The second is object vibration, in which a stationary worker interacts with a vibrating object in some fashion. It can affect motor control and visual performance. Motor control is mainly affected by the vibration intensity. Visual performance is mainly affected by the frequency.

6.3.5.5 Toxicity and air quality

The air quality in closed working places depends on parameters such as the external air quality, the air conditioning system design and its working conditions, the way the working place is partitioned and the amount and sort of pollutant sources. Some effects of bad air quality can be nausea, headaches, memory losses, concentration problems, evasive behaviour, hypersensitivity reactions among others.

6.3.6 Workplace Design

6.3.6.1 Facility layout

The layout of the plant should be such that it limits the risk to the lowest possible during operations, inspection, testing, maintenance, modification, repair and replacement. According to the COMAH Assessment Safety Report on Mechanical Engineering Aspects, evidence that these matters have been adequately considered in the design will usually be sufficient for the purposes of assessment. The plant design should provide enough safeguards to ensure safety and reliability even against excursions beyond design conditions. Safety report should show how systems which require human interaction have been designed to take into account the needs of the user and be reliable. Task and Link analysis can be very good tools in order to improve the facility layout.

6.3.6.2 Workstation configuration

The workstation is the area in which the person performs tasks and it is defined by the physical fixtures such as furniture, equipment, machinery, stairs or aisles among others and environmental variables such as lighting, vibration, temperature, toxicity or noise. Configuration of these places will refer to how the design is made to suit the characteristics of different individuals having to work in them.

6.3.6.3 Accessibility

A good workplace design allows people to physically reach all required equipment, tools and parts of the plant during operations, inspections, maintenance and/or repair. Workstation must be accessible to cranes as well as to workers with the clothing and tools required to work and they must ensure operators work in a comfortable way, without needing to crawl or stay in awkward positions while approaching the workstation or performing the task. This means that pathways to the workstation and the distance between adjacent equipment have to be large enough for this purpose.

6.3.6.4 Control room design

The room should be arranged in such a way that it best suits the operators' functions. A link analysis will show the relations between the operators in the control room and the equipment. Important aspects in the control room include lighting, noise, ventilation, communication and location

6.3.7 Operator characteristics

The operators' physical and cognitive characteristics, their skills, knowledge, attention, motivation, fitness for duty and competence will also have an influence on human error.

6.3.7.1 Skills and knowledge

Skills refer to how humans process and interpret the information. They are not inherent personal qualities and can be acquired through training and experience. They refer to the ability to recall and carry out each step of the task that has been assigned to them, technical reading and drawing skills, physical, cognitive, visual and hearing abilities. Knowledge requirements describe what the person needs to know and understand in order to satisfactorily perform the task for example knowledge of hazards, equipment, plant processes and operation procedures, rules and limits.

6.3.7.2 Attention/Motivation

The amount of stimuli that can be perceived by sensory systems is unlimited, but the amount of information that can be held in the working memory is limited to between five and nine items.

6.3.7.3 Fitness for duty

Fitness for duty is the ability to perform activities within an occupation or function to the standards expected in employment (Wright et al., 2002). This refers to matching individuals to tasks to ensure an adequate outcome. Individuals should be able to successfully undertake the specific tasks and activities to which they are assigned.

6.4 Qualitative Evaluation of Human Factors

The fault tree in figure 4-3 is going to be revisited in this subsection and the next chapters. The first three steps in figure 4-4 will be the main point of focus. The purpose of human factors analysis is to assign specific failure probabilities for each initiating event based on different underlying human factors on a selected incident. The existing models of present QRA have been taken as the basis for this new methodology. When an initiating event occurs a series of pivotal events 1 to N occurs before impact. Pivotal events could prevent, protect or mitigate the deviation or aggravate the situation.

Step 1: Identifying the causes of undesired event.

All the initiating events and basic events are identified using the conventional QRA methodologies. For this study an FTA is used, see figure 4-3. The top event "Major Flammable Release" which has a frequency of 3.2×10^{-2}/yr could be caused either by :

Spill during truck unloading	3.0×10^{-2}/yr
Tank rupture due to external event	3.0×10^{-5}/yr
Tank drain ruptures	1.0×10^{-4}/yr
Tank rupture due to implosion	2.0×10^{-3}/yr
Tank rupture due to overpressure	2.0×10^{-5}/yr

This classification is irrespective of the type of failure. If we look closely it is clear that events contributing most to the top event is spill during truck unloading (93.75%). This is one of the reasons we will concentrate on analysis of the event "Spill during truck unloading". The other reason is that this event has human error events in it. This value is the summation of all minimum cut-sets. Basic events B_1 (Insufficient volume in tank), B_2 (Level alarm fails or ignored) and B_5(Unloading frequency) make one minimum cut-set which has a frequency value of 3×10^{-2} $yr^{-1.}$. Minimum cut-sets are defined as set of basic events that contains no redundant elements (AIChE, 2000).

Step 2: Identifying initiating events with human error elements

This approach is striving in coming up with a systematic methodology to analyse the situation that may lead to human error. The approach should be able to predict the conditions that support the occurrence of error. This means we are shifting our attention from the error itself and focusing on the factors that support the occurrence of the error. From the fault tree analysis of flammable liquid storage tank, it was found that the following basic events contained human failure elements in them: Basic event B1: Insufficient Volume in Tank; B2: Level Alarm fails or ignored; B3: Wrong Material Fed into Tank; B4: Truck Tank not sampled before unloading and B5: Unloading Frequency.

These are typical events found during FTA. Not all basic events are classified as initiating events. Event B1 may not be classified as an initiating event but for the top event to occur this condition (filling the tank) has to be present. Any time the condition is present then an opportunity for error occurs. It is referred to as enabling event (AIChE, 2000).

Step 3: Identifying underlying human factor causes

Figure 6-9 represents the procedure to identify the underlying human factors. After the initiating events or hazardous conditions have been identified the human factors influencing these human error events are identified. One initiating event or basic event is analysed at a time. Each factor is considered to determine how much it could influence initiating event. The factors identified to have a "high" influence are given first priority, second priority goes to "moderate" and "low" gets the last priority. The reason for this classification is to limit the number of attributes to a manageable level. The maximum number of attributes recommended for the Analytical Hierarchy Process (AHP) is seven (Saaty, 2000). This method is going to be used for the quantification of human factors and is discussed in later chapters.

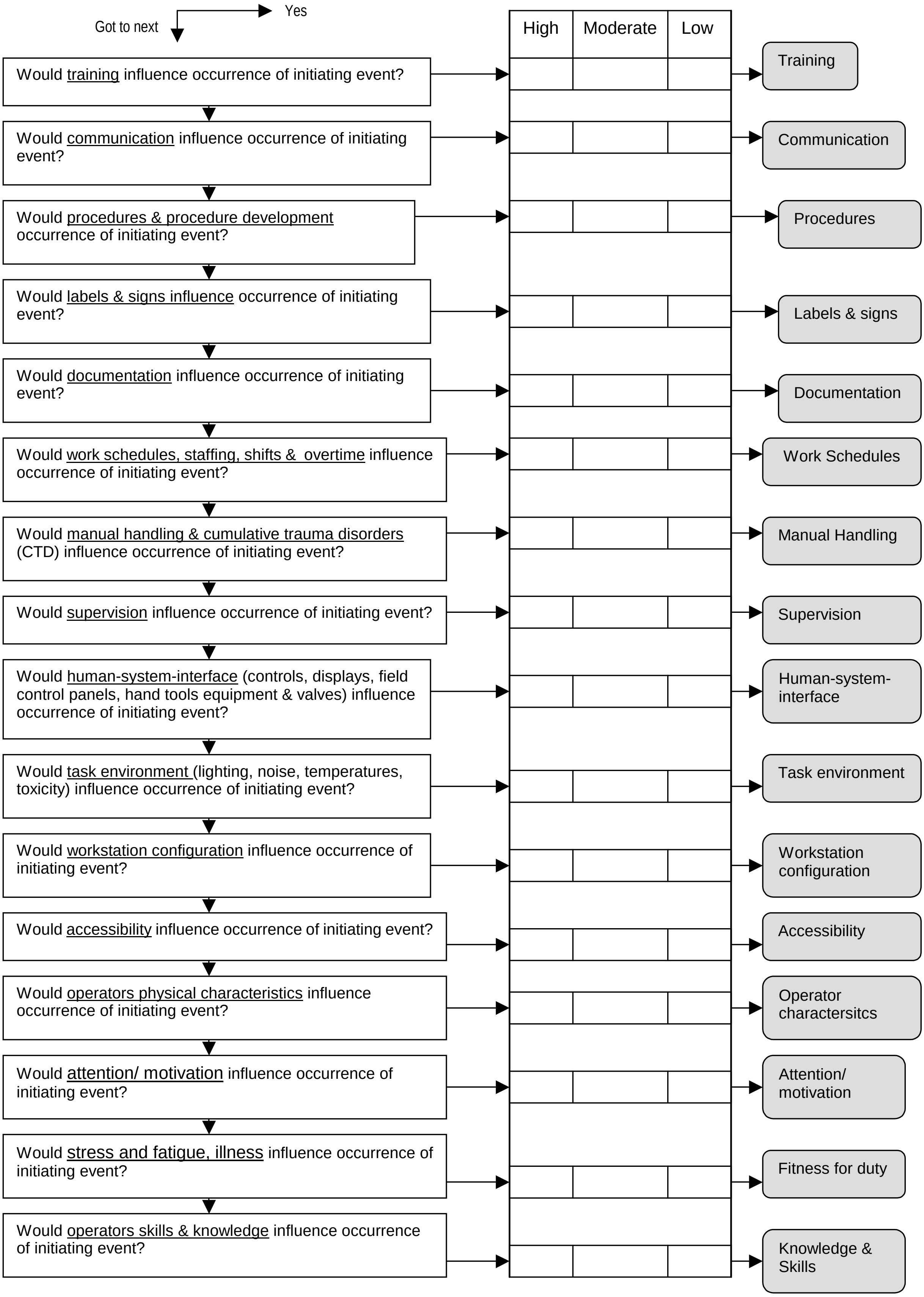

Figure 6-8: Procedure to identify the human factors underlying human error event (Kariuki and Löwe, 2006)

Table 6-2 illustrates a summary of attributes that may have significant impact on basic events B_1, B_2 and B_3. These have been identified using the procedure illustrated in figure 6-8. It is worth to note that this exercise is subjective and therefore may require input from several experts to make it valid.

Table 6-2: Attributes having significant impact on basic events B_1, B_2 and B_3.

	Information	Supervision	Human-System Interface Design	Task Environment	Workplace Design	Operator Characteristics
Basic Events						
B_1: Insufficient Volume in tank	Procedures Documentation Training	Checks	Displays			
B_2: High level alarm fails or ignored	Training		Displays	Lighting	Accessibility	Attention / Motivation Skills and Knowledge
B_3: Wrong material in tank	Documentation Labels & Signs	Checks				Attention/Motivation Fitness for duty

As an example, ordering procedures influence the volume that is available in the receiving tank. If documentation were not done adequately then ordering twice would be a feasible error. Job allocation determines the amount of workload on the operator. Supervision is another factor that needs to be analysed under this human error event. In this case task environment i.e. noise, heat, lighting, has no effect at all and so is the work place design. Each human error event identified as a cause of accident is analysed in the same way. The parameters or attributes identified will be used to modify the generic human error probabilities. The HF attributes should be specific enough to identify potential influences.

7 QUANTIFICATION OF HUMAN FACTORS AND INTEGRATION INTO QUANTITATIVE RISK ANALYSIS

7.1 Implementation of AHP in Overall Human Factors Assessment

7.1.1 Hierarchical Decomposition

The first step is to decompose human factors hierarchically. This is done as illustrated in fig 7-1. The aim of the decomposition is to find out the factors that influence the quality of human factors in a given plant. The overall objective is to maximise the quality index. This means that as the human factors index approaches maximum then the human performance is optimal and it will be reasonable to say that the rate of human error probability goes down. Through extensive literature review and consultation with experts from industry it has been found that the areas (referred here as factors) that have the biggest direct effect on this index are organisation, information, job design, human-system-interface, task environment, workplace design and operator characteristics. Each of these factors have attributes A1, A2,………, G3 and these are given in table 6-1. Attributes will be rated on a constructed scale with very poor on the lower side and excellent as the highest rating. While carrying out an assessment it is possible to see which of eight areas is rated as lacking or inadequate.

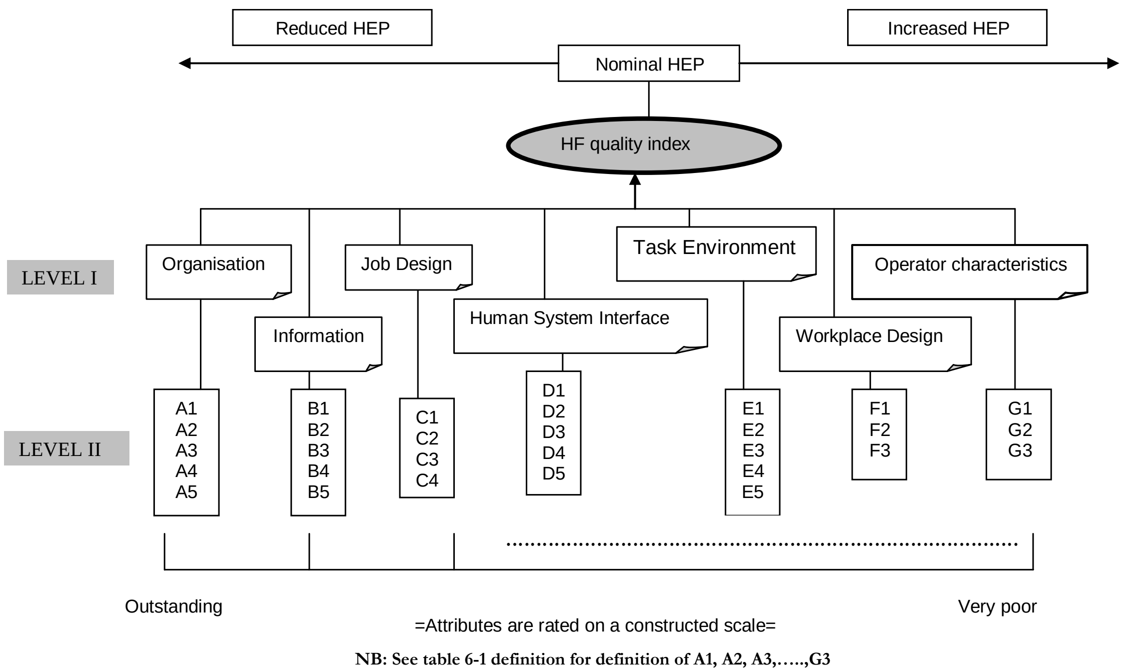

Figure 7-1: Hierarchical decomposition of human and organisational factors

This rating is desirable for decision-making purposes. The management will have a clear picture of the areas that need more resources for improvement. If the entire plant is rated as excellent then it will be reasonable to assume that the probability of operator error is reduced.

Although literature research revealed factors and respective attributes illustrated in table 6-1 and on fig 7-1, it is worth noting that some might have been left out. In addition, some analysts might feel that some of the attributes have been placed under a wrong factor or have been named differently. A refinement of this AHP structure will be recommended in order to address the above mentioned and other foreseeable shortcomings. The usability and validity of this assessment method is illustrated by use of an industrial example where the final version of the software was validated. It outlines step by step how an assessor would use it to make a decision whether a company has implemented human factors within its design and daily operations.

7.1.2 Elicitation of Weights

The purpose of this exercise is to develop a weighting system. The factors affecting the quality of human factors are multi-dimensional and therefore need to be ranked to determine how they affect the outcome. This weighting method is aimed at eliminating the dependence on ad hoc methods that do not adhere to the basic principles.

Operator error is a result of complex inter-relations of factors/attributes indicated on table 6-1. Each of these factors/attributes has a different weight of influence on operator error and this is what these matrices are striving to achieve. This process is repeated for all factors/attributes. The relative weights are then calculated before finally calculating the consistency ratio. For this purpose, a survey to seek opinion from experts in the industry was designed. The survey is described in the sections that follow.

7.1.2.1 The Questionnaire Formulation

The questionnaire was divided into two parts as shown in appendix B. The judges were asked to rate the factors in level I and attributes in level II according to the perceived importance towards human error causation. A five point Likert scale was chosen for this purpose with “least important = 1” being the lowest and “extremely important = 5” being the highest.

7.1.2.2 Selection of Judges

The judges or the respondents to the questionnaire were selected from the members of PRISM and the European Technology Platform on Industrial Safety (ETPIS). The choice was based on the fact that most members have a background on both safety and HF. Out of all the respondents 23 judges were selected. They were distributed across the following industries: 9 judges from chemical & petro-Chemical (including pharmaceutical), 4 from academic and research institutes, 4 from oil & gas (Upstream), 2 from nuclear and 1 each from health, mining, construction and rail. The representation from all industries is to make this weighting as diverse as possible. But it should be noted that the number of judges from the chemical process industry and oil & gas outclasses the others since the focus of this study is on these industries. The average years of experience was 18.52 (standard deviation, 7.97 and range 4 to 33).

7.1.2.3 Analysis of the results

The degree of importance given to each human factor by all the 24 judges and the author is presented in table 7-1. The weighting was very close for all judges except in few cases where the standard deviation was beyond 1. The first case where standard deviation was high (1.34) was in "Human factors and Safety Policy". Major difference was contributed by judge 1, judge 11 and judge 13 who weighted this factor in the category of least important. An explanation to this could be because judge 1 comes from the health industry and therefore the approach to safety may differ from that of the chemical process industry.

Judge 13 is a contractor to the oil and gas industry. There has always been a bone of contention between the contractors and the industry especially in the organisational matters. Contractors are sometimes seen as safety threats because they often view safety measures laid down by the industries as hindrances to their effective work. Therefore, when weighting the organisational matters it is expected that a contractor will tend to be biased.

Table 7-1: Judges Weighting of the HF Spectrum

		Judge																								
	Author	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Average	STD Deviation
Organisation & management	5	2	4	5	5	5	2	3	5	5	5	3	4	4	5	2	5	4	4	4	4	4	4	5	4.08	1.00
Information	3	3	4	4	4	4	2	4	4	4	4	4	2	4	4	3	4	5	3	4	3	5	4	4	3.71	0.73
Job Design	3	4	3	4	3	3	3	4	3	4	5	3	5	4	4	4	3	4	2	4	3	5	3	4	3.63	0.75
Human System Interface	4	4	3	3	3	4	4	4	4	4	4	3	2	4	3	5	2	5	4	3	3	4	4	4	3.63	0.75
Task Environment	3	3	3	4	2	4	3	2	1	4	4	4	2	2	2	5	2	4	2	3	4	5	2	2	3.00	1.08
Workplace Design	3	5	3	4	2	4	3	5	1	4	4	3	4	4	2	5	3	3	2	3	3	5	3	2	3.33	1.07
Operator Characteristics	2	2	5	3	4	5	4	4	3	4	4	2	3	5	4	4	1	3	2	5	5	5	5	4	3.67	1.18
Human factors and safety policy	5	1	2	4	5	4	3	4	3	4	3	1	4	1	3	5	4	4	5	4	3	4	3	5	3.50	1.22
Organisational culture	3	2	4	5	5	5	4	3	4	5	5	4	2	4	5	3	3	3	3	4	3	4	4	5	3.83	0.94
Management of change	4	2	3	3	4	3	4	2	5	5	5	4	2	3	4	3	2	4	4	4	4	4	5	5	3.67	0.99
Organisational learning (audit & reviews)	4	2	4	4	4	4	4	3	3	4	4	2	4	3	4	3	3	3	4	3	3	4	3	5	3.50	0.71
Line management & supervision	3	3	3	3	5	4	4	5	1	4	4	3	4	4	4	4	4	4	5	3	4	4	4	5	3.79	0.87
Training	4	3	3	4	4	5	4	4	4	4	4	4	5	4	5	4	3	5	5	3	4	5	5	3	4.08	0.70
Procedures & procedure development	3	3	3	5	4	3	3	4	3	4	3	4	4	3	4	5	4	4	3	3	3	5	3	3	3.58	0.70
Communication	4	3	5	4	5	4	4	4	4	4	4	4	4	4	4	4	5	5	3	4	4	5	4	4	4.13	0.53
Labels & signs	2	4	1	3	4	4	3	3	2	3	3	1	2	4	2	4	4	5	3	4	4	3	3	2	3.04	1.02
Documentation	2	3	2	3	4	3	3	2	3	4	4	1	5	4	3	4	2	4	2	4	4	4	4	2	3.17	0.99
Staffing	2	4	3	3	3	3	4	4	2	5	3	3	4	4	5	3	2	4	3	3	4	4	3	4	3.42	0.81
Shifts & overtime	2	4	3	3	3	4	4	4	2	3	4	4	5	2	2	3	3	5	2	3	3	4	4	4	3.33	0.90
Manual handling.	2	3	1	3	4	3	4	4	1	3	3	1	4	3	1	3	2	3	1	2	4	5	2	2	2.67	1.14
Design of controls	4	4	2	4	3	4	4	3	2	5	2	4	4	4	3	5	2	5	3	3	3	3	3	3	3.42	0.91
Displays	4	4	2	3	3	5	3	3	5	4	2	3	5	4	4	5	3	5	4	3	3	3	4	3	3.63	0.90
Field Control Panels	4	4	2	3	2	3	4	3	4	3	2	3	4	4	3	5	2	5	2	3	2	3	4	3	3.21	0.91
Tools (hand)	4	3	2	3	3	4	4	4	3	4	2	1	5	4	2	4	2	4	4	3	4	4	3	3	3.29	0.93
Equipment & valves	4	4	2	3	2	3	3	2	3	4	2	3	2	4	2	4	2	4	2	3	3	4	3	3	2.96	0.79
Lighting	2	2	3	4	3	4	3	3	2	3	2	2	5	2	2	4	3	4	2	4	4	5	3	4	3.13	0.97
Temperatures	2	2	3	4	2	4	4	5	1	3	2	3	4	2	2	4	3	3	2	4	4	5	2	4	3.08	1.08
Noise	2	2	4	3	2	3	4	4	4	1	2	4	4	1	2	4	4	3	2	4	4	5	4	4	3.17	1.11
Vibration	2	2	4	3	2	3	4	4	4	1	2	4	4	1	2	4	4	3	2	4	4	5	4	4	3.17	1.11
Toxicity	2	1	3	3	2	3	3	5	5	3	4	1	5	3	2	4	2	4	1	5	5	5	2	4	3.21	1.35
Facility Layout	3	4	3	4	2	4	3	3	3	3	4	3	4	3	1	4	3	3	2	4	3	4	3	4	3.21	0.76
Workstation configuration	3	5	2	4	2	3	3	3	2	3	4	4	5	3	2	4	2	3	3	4	3	4	3	3	3.21	0.87
Accessibility	3	4	2	4	3	4	2	4	1	3	3	2	5	3	2	4	4	4	3	4	4	4	2	3	3.21	0.96
Control Room	2	5	2	4	2	5	3	3	2	3	4	4	5	3	2	4	3	5	3	4	4	4	3	4	3.46	1.00
Attention/ motivation	2	4	5	3	5	5	3	5	5	5	4	4	4	5	4	4	4	4	5	4	5	5	5	5	4.33	0.80
Fitness for duty	4	4	3	3	4	2	4	3	3	4	4	3	5	3	3	5	3	3	3	3	5	5	4	5	3.67	0.85
Skills and knowledge	3	4	5	4	4	4	5	4	5	5	5	4	5	5	4	5	3	2	4	3	5	5	5	4	4.25	0.83

7.1.2.4 Normalising Weights assigned by Judges' Using AHP

The first step is to convert the Likert scale used for the questionnaire to matrices of pairwise comparison. Let's take an example using table 7-2, which are results obtained from judge 8. The judge weighted both "Task Environment" and "Workplace design" in the category of least important. Since both of them fall in the same level then they are "equally important" (see table 5-1). "Information" is moderately more important than "job design" because it (information) falls one level higher. "Organisation & management" has been weighted as extremely important when compared with "task environment" or "workplace design". A matrix of pairwise comparison obtained from table 7-2 is shown in table 7-3.

Table 7-2: An Example from the Questionnaire Response

	Least important	Important	Moderately important	Highly important	Extremely important
Organisation and management	☐	☐	☐	☐	☒
Information	☐	☐	☐	☒	☐
Job Design	☐	☐	☒	☐	☐
Human System Interface	☐	☐	☐	☒	☐
Task Environment	☒	☐	☐	☐	☐
Workplace Design	☒	☐	☐	☐	☐
Operator Characteristics	☐	☐	☒	☐	☐

Table 7-3: Matrix of Pair-wise Comparison using AHP

	ORG	INFO	JD	HSI	TE	WD	OP	Relative Weight
ORG	1	3	5	3	9	9	5	0.39
INFO		1	3	1	7	7	3	0.19
JD			1	1/3	5	5	1	0.09
HSI				1	7	7	3	0.19
TE					1	1	1/5	0.03
WD						1	1/5	0.03
OP							1	0.09
Consistency index								0.04

This exercise was repeated for all the factors and attributes as weighted by the judges. Matrices of pair-wise comparison are developed for the factors and their respective attributes. These factors/attributes are compared against each other to determine the relative importance. A total of 8 matrices were produced for each judge. One matrix corresponding to level I of the hierarchy and 7 matrices for level II. The matrices were found to be relatively consistent with the consistency ratio ranging from 0 to 0.06. The relative weights for each factor and attribute obtained from the matrices of pair-wise comparison were averaged to obtain the mean relative weights. These are illustrated in appendix B tables, B-3 and table B-4. Table 7-4 illustrates the results obtained for the factors/attributes that need to be considered while assessing the quality of human factors in a given facility. The weights are important aid to decision making on where more effort or resources should be directed. Global weight is obtained by combining the relative weights down a branch of the hierarchy. These are illustrated graphically in figure 7-2.

Attention/ motivation has emerged the attribute with the highest weight. The judges feel that this particular attribute contribute to most human errors and consequently to most incidents in the process industry.

Table 7-4: Relative and Global Weights of Critical Human Factors and Attributes

Factors	Relative Weight	Attribute	Relative weight	Global Weight
Organisation	0.21	HF Policy	0.17	0.036
		Organisational culture	0.24	0.051
		Management of change	0.20	0.042
		Organisational learning (audit & reviews)	0.16	0.033
		Line management & supervision	0.22	0.047
Information	0.14	Training	0.27	0.038
		Procedures & procedure development	0.18	0.025
		Communication	0.27	0.038
		Labels & signs	0.14	0.019
		Documentation	0.14	0.020
Job design	0.13	Staffing	0.38	0.049
		Shifts & overtime	0.40	0.051
		Manual handling.	0.23	0.029
Human System Interface	0.13	Design of controls	0.22	0.029
		Displays	0.26	0.034
		Field control panels	0.18	0.023
		Tools (hand)	0.20	0.027
		Equipment & valves	0.14	0.018
Task Environment	0.09	Lighting	0.19	0.017
		Temperatures	0.19	0.017
		Noise	0.19	0.017
		Vibration	0.18	0.016
		Toxicity	0.25	0.022
Workplace Design	0.13	Facility layout	0.25	0.032
		Workstation configuration	0.24	0.031
		Accessibility	0.27	0.036
		Control Room	0.24	0.031
Operator Characteristics	0.18	Attention/ motivation	0.42	0.076
		Fitness for duty	0.21	0.038
		Skills and knowledge	0.37	0.066

Lack of attention/motivation by the operator is usually a symptom of a deeper problem. Errors caused by lack of attention/motivation are due to lack of situation awareness, failure to detect information or operator memory slips/lapses. If the human system interface is inadequately designed, then information presented to the operator does not provide the entire situation awareness. It is therefore hard to interpret results especially during emergency situations. If procedures are unclear then they could also contribute to such errors. Training plays a major role in preventing or reduction errors due to lack of attention. Also factors like personnel selection, monitoring and performance evaluation contribute to attention/motivation when not adequately done. Performance evaluation helps to detect where training is needed most. When designing error prevention strategies focus should be on these underlying factors.

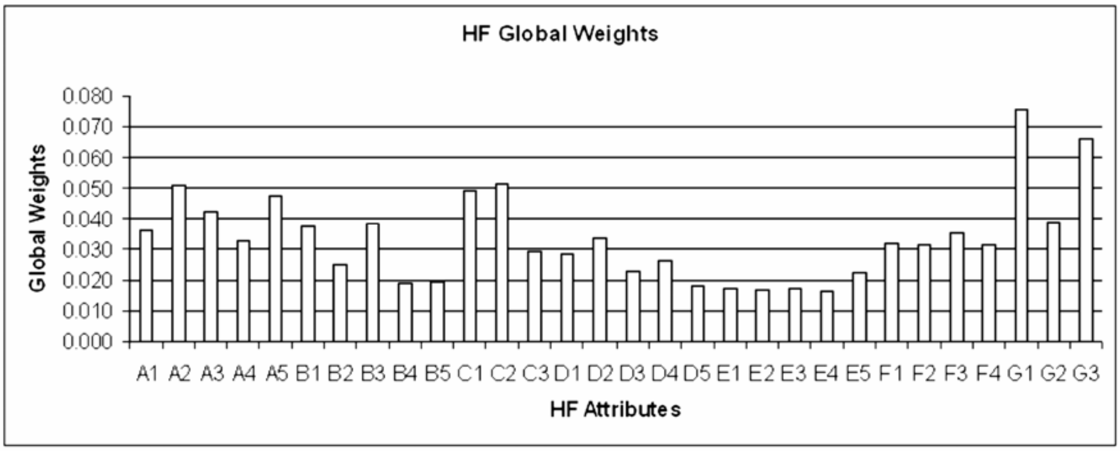

Figure 7-2: Resulting HF Global Weights (A1, A2….., G3 are defined in Table 6-1 on pg 61)

Another area given high weighting is "skills and knowledge". Lack of proper skills and knowledge is contributed by lack of proper training. If proper training is not provided or is infrequently provided then errors due to lack of skills and knowledge could be common. Similarly "organisational culture" has received a reasonably high weighting.

"Shifts & overtime" was also rated high because it is felt that it contributes to operator stress and fatigue. It is also noted that the shifts handover contribute to a high number of errors that could lead to accidents. An example was the Piper Alpha disaster described earlier.

The next step is to develop a rating system. It is the tool to be used by the assessor to valuate various facility attributes. The rating value obtained is to be multiplied by respective global weight of this attribute. The separate contributions of each attribute to the overall objective (score) are considered to be additive. That is, the overall human factors quality index, HFQi is defined as the sum of products of all individual attribute's weight and their respective performance measures also referred to as rating. (Kariuki and Löwe, 2005):

$$\text{HFQi} = \sum_{i=1}^{n} \omega_i v_i(x_i) \tag{7.1}$$

Where, $v_i(x_i)$ is a value function of attribute x_i represented by a rating (also referred to as performance measure) r_i. HFQi is a cardinal numerical score. The score trades off different levels of performance among attributes in a compensatory way, by using the cardinal weight ω_i calculated using matrices of pair-wise comparison and by characterising each attribute numerically.

The attributes x_i of the facility being assessed are rated using a five-point Likert scale. Likert scale is type of a psychometric response scale often used in questionnaires and is the most widely used in survey research. These rates are the performance measures of the plant (facility) and they indicate the general characteristics in terms of operability and maintainability. High operability and maintainability means consistency of errorless task performance. The better they are the higher the HFQi and therefore the lesser the risk. The ratings are represented by r_1, r_2, …..,r_n and are assigned a scale 1 – 5, where 1 represents the worst performance measure and 5 represents the best, see fig 6-3.

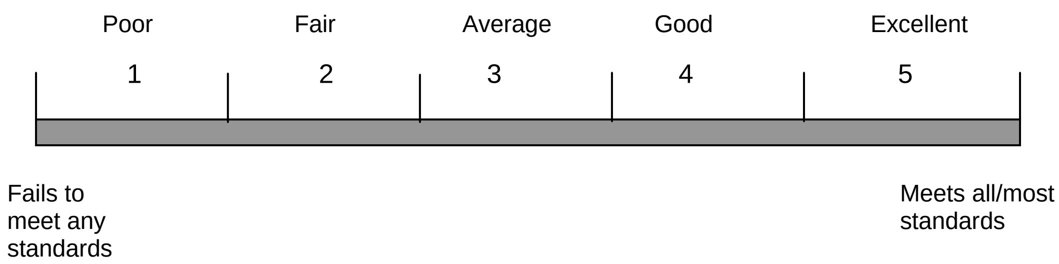

Figure 7-3: Five-point scale for rating attributes

The rating of the attributes is guided by a series of questions that have been developed. The questions cover all the 30 human factors attributes, A1, A2, …., G3. They are structured in a way that they do not attract a simple yes/no answer. Attached to each answer is supporting evidence to strengthen the answer given. Evidently the rating exercise may be characterised by biasness if one assessor is used. To reduce this weakness more than one analyst should carry out this task.

These rates are multiplied by the global weights before finally adding the weighted scores to achieve the overall objective. If a company attained a maximum score in all areas then the HFQ_i assumes a value of 1. Any other score is a fraction of this maximum value. The range of various human factors quality indices is tabulated in table 7-5.

Table 7-5: Overall range of human factors quality index

Human Factors Quality Index	Description of HFQ_i
More than 90%	Excellent
77.6% – 90%	Above average
60.6% – 77.5%	Good, Average
46% – 60.5%	Below Average
45% or less	Poor

7.2 Human Factors Assessment Technique Software

Based on the above background computer interface was designed and built to guide and help the user through the assessment (Vadillo, 2006). The computer programme also calculates automatically the score of the plant, company or industry under assessment. The programme was written in Excel using Visual Basic Language. Excel was considered sufficient because it had computing capabilities to cover the needs for this particular task. Mathematical algorithms were programmed for calculating the weighting factors of each one of the attributes and the overall human factors quality. Then a user interface was designed. This user interface consists of eight input datasheets (one for each group of human factors) and three output datasheets.

7.2.1 How to Use the Programme

The programme is called PIHFAT (Process Industry Human Factors Assessment Technique).

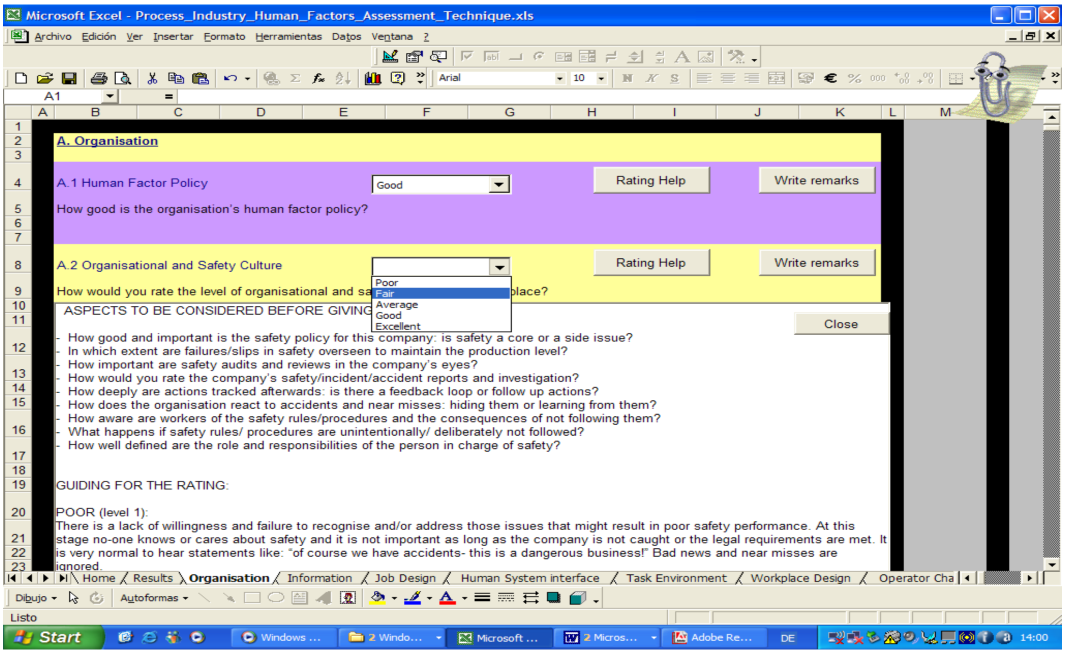

Figure 7-4: User Interface "Organisation"

There are seven input datasheets, one for each group of human factors. We take "Organisation" as an example. On this page all the attributes under the factor "Organisation are shown, A1 to A5. Under each attribute is a rating question e.g. "How good is management of change in this company". It is clear that this question cannot be answered with a no or yes and that is where the scale of "Poor" to "Excellent" applies. On the same worksheet there is a "rating help" icon. It provides additional questions that guide the assessor in making his/her decision. The assessor is also provided with an opportunity to write any observations made during the assessment procedure. This is done by clicking on the "write remarks".

After all the input fields have been made the assessor can go to the worksheet "results". It has two modes of outputs. The first is numerical output which shows the HFQi as a percentage (see figure 7-6) and this can be interpreted using table 7-5.

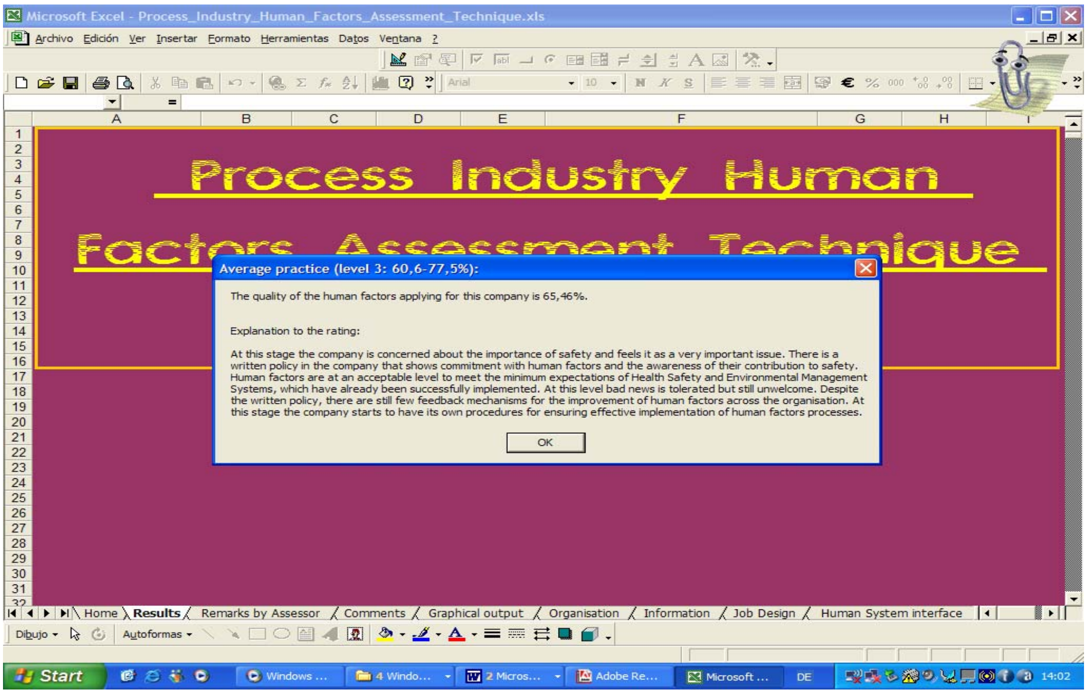

Figure 7-5: User Interface "Results"

By clicking on "comments" the author would see the rating by each attribute and the corresponding interpretation of each score. There is a possibility to display the results graphically. This shows how each attribute has faired in the rating. From figure 7-6 it is visible that "staffing", "schedules, shifts and overtime" and "design of controls" have scored poorly and therefore focus on improvement should be directed to them.

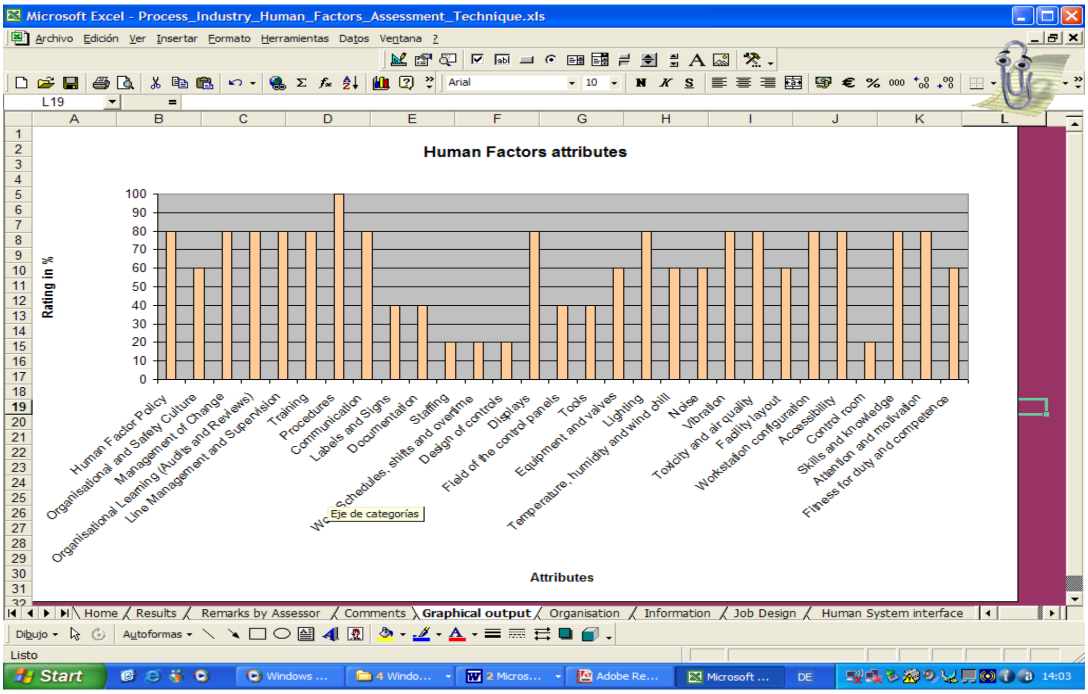

Figure 7-6: User interface "Graphical Output"

7.3 Integrating human factors into QRA

7.3.1 Introduction

The previous part was concerned with assessing the whole HF spectrum. But during the QRA we are concerned only with factors that affect the operator performance of a particular task, otherwise known as PIFs. Once a potential human error event has been identified, the factors that could influence its occurrence are identified and quantified. Each factor identified will be assigned a weight ω_i', which represents how much it contributes towards human error occurrence. This new weight is calculated as shown in Table 7-7 on page 91. The weights help to calculate human factors modification index which is used to adjust the nominal human error probability to reflect the plant conditions. The procedure can be summarised as shown in figure 7-7.

The building block for this method is the existing risk analysis methods. Fault tree as has been mentioned earlier will be used. To undertake a QRA the probability of initiating events and the basic events need to be assigned. For example "operator fails to close valve". There is a shortage of HEPs data and the ones that exist is plagued with high uncertainty. Introducing plant specific factors is to try and reduce this uncertainty. This is especially useful in cases where the probability ranges have been generated by use of expert judgment.

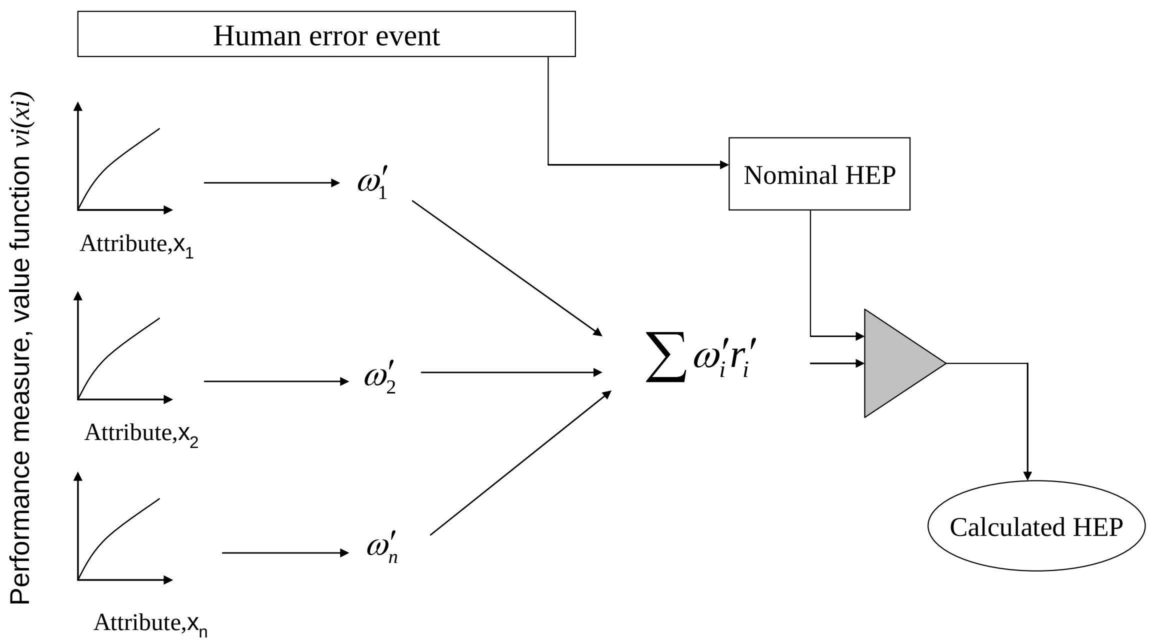

Figure 7-7: Modification of Human Error Probabilities by use of weighted performance influencing factors.

7.3.2 Calculating the human factors modification indices

From weights ω_i' and performance measures r_i', the human factors modification index for each human error event is calculated. The factors affecting initiating or basic events are identified before the quantification process starts. The factors influencing human performance have been identified as organisation, information, job design, human machine interface, task environment, workplace design and operator characteristics and these are illustrated on figure 7-1 (pg 76) and each of these has accompanying attributes. Revisiting the fault tree, it was found that the following basic and initiating events have human error events in then:

B1: Insufficient Volume in Tank;
B2: Level Alarm fails or ignored;
B3: Wrong Material Fed into Tank;
B4: Truck Tank not sampled before unloading and
B5: Unloading Frequency.

For the event, "insufficient volume in tank", the following were identified as the influencing factors:
-Procedures
-Documentation
-Training
-Checks
-Displays

For the other events the influencing HF are tabulated in table 6-2. All influencing factors should be identified for each error event. A weighting system is developed for the factors behind each human error event identified. A combination of weighting factors and performance measure will constitute what we have defined as human factors modification index:

Human modification factors index,

$$\beta = \omega_1' r_1' + \omega_2' r_2' + \ldots\ldots\ldots\ldots + \omega_n' r_n'$$

$$= \sum_{i=1}^{n} \omega_i' r_i' \qquad (7.2)$$

Where ω_i' = weight of each attribute behind a human error event.

r_i' = Value function (performance measure) of attribute $x_{i.}$

β is important in adjusting the nominal/ base rate HEPs to reflect the specific conditions of a plant. The aim is to reduce uncertainty in HEPs as much as possible. The uncertainty range is described by error factor EF in most HRA methods e.g. THERP (Swain and Guttman, 1983), HEART (Williams, 1986) and CREAM (Hollnagel, 1998). In this method, human error data from these sources (mainly from Swain) is going to be used. In addition values from expert judgment may be also be used in some cases. Error factor is defined as the square root of the upper to the lower uncertainty bounds/ limits. This uncertainty range is contributed by the fact that each HEP estimate is associated with some degree of uncertainty and therefore is represented by a distribution rather than a single point estimate. The distribution of HEPs is assumed to be lognormal because performance of skilled personnel tends to be skewed towards the low HEP end of HEP distribution. The nominal probability is considered to be the mean of lognormal distribution. It represents the condition where the plant conditions lies within the industry average. A selected range of HEPs is shown in table 7-6.

Table 7-6: A selected HEPs ranges for different human error events

Human Error	Nominal HEP	Error Factor	HEP Distribution Range
General error rate given very high stress levels and activities are occurring rapidly	0.3	3	0.1 – 0.9
Inspector fails to detect undesired position of valve during walk round inspection	0.5	3	0.1 - 1
Incorrect installation of O ring	0.07	5	0.01 – 0.35
Failure to follow instructions	0.07	5	0.01 – 0.35
Improperly adjusting mechanical linkage	0.02	10	0.002 – 0.2
General human error of omission e.g. failure to return manually operated test valve to proper configuration after maintenance	0.01	10	0.001 – 0.1
Incorrect reading of gauge	0.005	10	0.0005 – 0.05
Installation of wrong size of line orifice, incorrect hose connection, incorrect tightening of bolts or nut.	0.005	10	0.0005 – 0.05
General human error of commission e.g. selecting a wrong switch	0.003	10	0.0003 – 0.03
Omission of action embedded in a procedure	0.003	10	0.0003 – 0.03
Failure to close valve properly	0.0015	10	0.00015 – 0.015
Failure to take action, failure to observe audible alarm	0.0003	10	0.00003 – 0.003

The lognormal model used by Swain is multiplicative and only mathematically correct to a first application. Lets consider, for instance, the error probability of 0.5 (EF = 3). The actual value of the upper bound is 1.5 but as we know the maximum probability value is 1. It is possible to reduce this shortcoming by introducing an odds ratio which is considered more mathematically correct.

Lets the probability of failure be denoted by P, such that the success probability Q = 1 – P. Therefore odds ratio Y = Q/P. The uncertainty can be modeled using true multiplicative variable

$$p = 1/\ (1 + y) = 1/\ (1 + e^{x})$$

Here:

Y = Lognormally distributed variable where y = (1 – p) / p as the median with EF as the uncertainty factor

p = point estimate of human error probability referred to as nominal human error probability in Swain's Handbook.

EF = uncertainty/ error factor of p (obtained from the handbook)

X = normally distributed variable with $\mu = \ln y$ and $\sigma = (\ln EF)/1.645$

Lets take the case where probability of failure p = 0.5, then the odds ratio will acquire a value y = 1. It is indicated that the EF from Swain's handbook , EF = 5. The lower bound (LB) and upper bound (UB) for this example can then be calculated as follows:

LB = 1 / (1 + y*EF) = 1 / (1 + 1*5) = 0.17

UB = 1 / (1 + y/EF) = 1 / 1 + 1/5) = 0.83

This model is more exact because the point estimates from Swains Handbook are actually median values for a lognormal distribution. In this type of distribution the mean is usually larger than the median and therefore it would be inaccurate to take the nominal HEP as the mean of a lognormal distribution.

Since the aim is to reduce the uncertainty margin to reflect the current plant conditions, the adjustment is done using the following formula.

$$HEP_{calculated} = HEP_{UB} 10^{\Theta\beta} \qquad (7.3)$$

Where, Θ = Log HEP_{LB} – Log HEP_{UB} and

HEP_{UB} and HEP_{LB} are the upper limit /bound and lower limit / bound human error probabilities respectively.

See an illustrative example in section 7.3.4

7.3.3 Calculating Weights

The weights ω_i' are calculated from results achieved from the questionnaire. Table 7-4 shows the weights when comparing the whole HF spectrum. But in this case when calculating weights we are concerned with the factors that directly influence the human error event under consideration. These factors are identified using the procedure described on section 6.6. Weights are selected from table 7-4 and then normalised. This is an advantage of this method. It allows combination of different factors to be calculated to suit specific scenarios. We revisit the basic events that contribute to the spill of hydrocarbon as described using the fault tree. These are tabulated on table 7-7 and it can be observed that weights have been calculated depending on the event under consideration.

Table 7-7: Basic events with human error event

	Identified Influencing factors	Weights from table 7-4	Normalised weights, ω' i
Basic event 1	Procedures	0.025	0.15
Insufficient volume in tank	Documentation	0.020	0.12
	Training	0.038	0.23
	Supervision checks	0.047	0.29
	Displays	0.034	0.21
		Sum = 0.164	Sum = 1
Basic event 2	Displays	0.034	0.13
High level alarm fails or ignored	Lighting	0.017	0.06
	Accessibility	0.036	0.14
	Attention / Motivation	0.076	0.28
	Skills and Knowledge	0.066	0.25
		Sum =0.267	Sum = 1
Basic event 3	Documentation	0.020	0.10
Wrong material in tank	Labels & signs	0.019	0.10
	Supervision Checks	0.047	0.23
	Attention/Motivation	0.076	0.38
	Fitness for duty	0.038	0.19
		Sum = 0.2	Sum = 1

7.3.4 Rating the attributes of a facility and adjusting the HEPs

The performance measure, r_i' is obtained by carrying out an audit. When doing an audit it is recommended that the whole human factors spectrum be covered. From such an audit it will be possible to pick any r_i'. The procedure for obtaining the performance measure value is the same as that described in section 7.1.2.4 on page 83. The performance measures are then combined with the normalised weights, ω_i' to obtain the HF modification indices, β. This is what will be used to adjust the respective nominal or base HEPs. For the purpose of quantification and adjustment of HEPs, the scale to be used is going to be a little different from the one on fig 6-3. It remains a five-point Likert scale but in this case excellent conditions assume 1 and poor assume 0. Average conditions will be assigned 0.5.

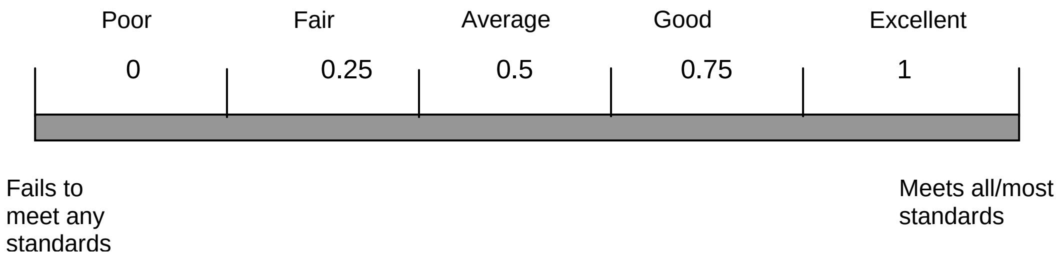

Figure 7-8: The scale showing human factors rating

The basic event "Insufficient volume in tank" has the influencing factors procedures, documentation, training, supervision and displays and these are tabulated on table 6-6. The respective weights are also shown. This type of human error event is a typical error of omission with a probability range between 0.01 (EF=10). Using odds ratio:

y = (1-p) / p = (1-0.01) / 0.01 = 99

LB = 1 / (1 + y.EF) = 1/991 = 0.001

UB = 1 / (1 + y/EF) = 1 / 10.9 = 0.09

If we set the rating for all factors to be excellent (1) and poor (0) then β will be 1 and 0 respectively.

i.e. β = (0.15 + 0.12 + 0.23 + 0.29 + 0.21) x 1 = 1

and (0.15 + 0.12 + 0.23 + 0.29 + 0.21) x 0 = 0

Using equation 7.3 it can be shown that $HEP_{calculated}$ under these conditions is 0.09 when all factors are rated poor and 0.001 when all the factors are rated excellent.

$$HEP_{calculated} = 0.09 * 10^{(\log 0.001 - \log 0.09)\beta}$$

Where, β = 0 or 1

A representation of how the HEP varies (0.001 – 0.09) with the change in HF conditions (from poor to excellent) is illustrated in fig 7-9. It is seen that when the human factors conditions change from poor to fair the HEP reduces from 0.09 to 0.03 and from poor to average it improves from 0.09 to 0.009. In this case all human factors ratings are held constant in each case.

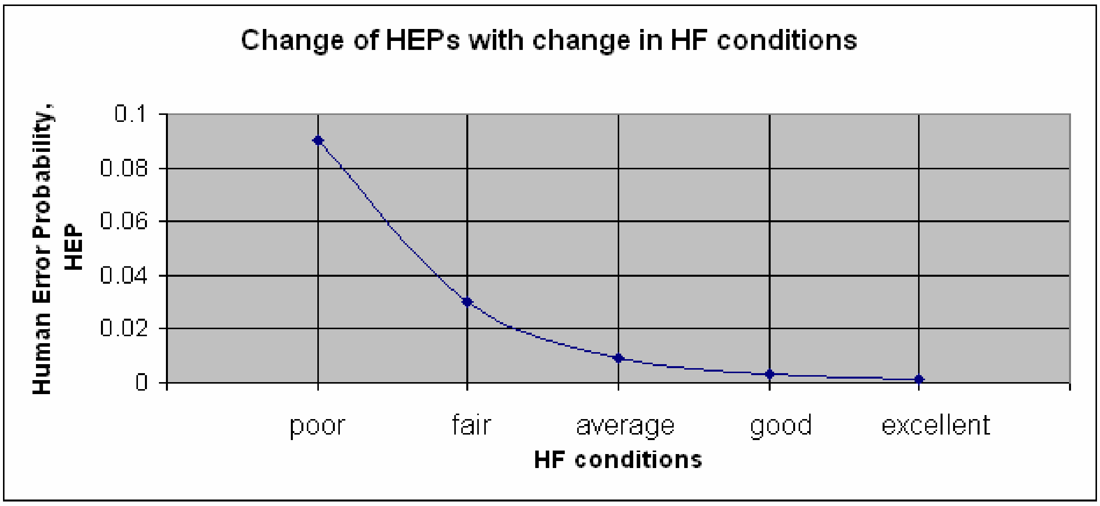

Figure 7-9: Distribution of Human Error Probability depending on the influencing factors

Revisiting the fault tree, it was earlier mentioned that the minimum cutset with the greatest influence on the top event is contain basic events B_1, B_2 and B_5. The HEP range for B1 (0.001 – 0.09) has been described above. The same case applies to event B_2 since both have the same nominal HEP. Event B_5 (Frequency = 300/yr) will be assumed to remain constant since this depends on the number of times the tank is loaded. It may not be included in the error reduction strategy because it would be difficult to influence the number of unloading per year. It is dependent on operational requirements and therefore beyond the boundaries of hazard analysis.

We will use results of an analysis done on two facilities (Kariuki and Löwe, 2006) to calculate the human factors indices, β for each of the two basic events B_1 and B_2. This is done using equation 7.2 and results are tabulated on table 7-8. It is seen that the factors associated with the occurrence of the human error events, B_1 and B_2 are below industry average for facility A while those for facility B are above the industry average.

Table 7-8: Calculation of human factors index for two facilities

	Identified Influencing factors	Normalised weights, ω_i'	Facility A, r_i'	Facility B, r_i'
Basic event 1	Procedures	0.15	1	1
Insufficient volume in tank	Documentation	0.12	1	1
(HEP range = 0.001 – 0.09)	Training	0.23	0.5	1
	Supervision checks	0.29	0.25	0.5
	Displays	0.21	0	1
			β =0.46	β =0.86
Basic event 2	Displays	0.13	0	1
High level alarm fails or ignored	Lighting	0.06	0.25	0.25
(HEP range = 0.001 – 0.09)	Accessibility	0.14	0.25	0.75
	Attention / Motivation	0.28	0.25	0.25
	Skills and Knowledge	0.25	0.75	0.75
			β =0.31	β =0.51

Using equation 7.3, for both basic events Θ = -2.

Taking basic event 1,

$HEP_{calculated}$ = 0.012 for facility A and 0.002 for facility B.

For basic event 2,

$HEP_{calculated}$ = 0.024 for facility A and 0.01 for facility B.

Let us look at the implications of this analysis. The original FTA has used the industry mean. That is, the logarithmic mean of the probability distribution. In this case the cutset $B_1.B_2.B_5$ = 3 x 10^{-2}/yr. In our analysis the plant specific conditions have been introduced. The results have shown a very big difference between the value of the same cutset in facility A and facility B. For facility A the cutset $B_1.B_2.B_5$ = 8.6 x 10^{-2}/yr.

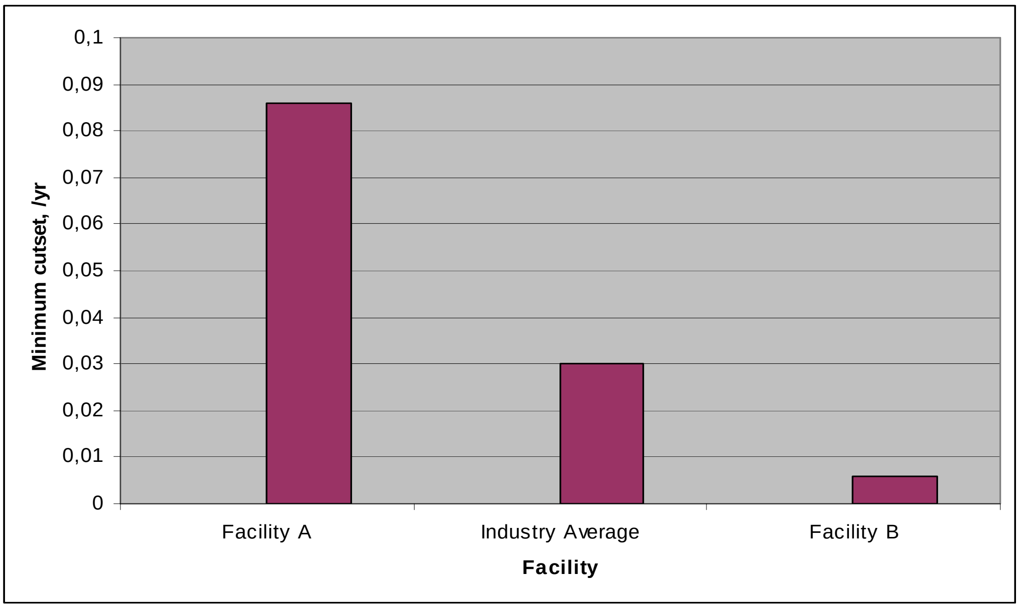

Figure 7-10: Comparison of a minimum cutset for different facilities

Had the industry average been taken for this facility the risk could have been underestimated by a factor of close to 3. The same cutset has a value of 6×10^{-3}/yr in facility B. For risk reduction strategies it is clear that displays require special attention for facility A. Also the factors that affect attention and motivation should be addressed since this attribute has a big weight.

8 CONCLUSIONS AND RECOMMENDATIONS

In this work the application of Human factors as a way of reducing unwanted events was discussed. It has been made clear that there are existing laws and regulations, specifically, SEVESO II directive that calls for the implementation of human factors as a way of reducing risk. However, as part of this work a study was carried out within the European chemical process industry and results showed that most companies are still at the lower capability level when it comes to understanding and implementing HF. Obstacles hindering the achievement of this goal were identified. One of the identified obstacles was lack of a systematic method to include HF in the quantitative risk analysis. This is what this work has achieved.

Human reliability analysis (HRA) is a subject that has been under discussion for a very long time. Scarcity of human error probability (HEP) data and uncertainty in the existing data have deterred the HRA methods to reach there maturity when compared to reliability analysis methods for technical systems. In the chemical process industry the sources of HEP data are mainly from the nuclear industry and expert judgement. And as long as the shortage of HEP data continues these two sources of data will remain useful. When carrying out a standard quantitative risk analysis, the practice is to take the nominal HEP as the best estimate. This in some cases leads to either under or overestimation of risk. The major concerns are when the risk is underestimated. It has been argued in this work that the inclusion of plant specific conditions will reduced the uncertainty that characterises the HEPs.

The new method was accomplished in two phases. First, a computer-based assessment tool called Process Industry Human Factors Assessment Technique (PIHFAT) was developed. PIHFAT can be used as a standalone HF auditing tool for auditing the quality of HF in a given plant. The basis of this tool was a classification of HF which consisted of breaking down the whole spectrum into 30 attributes. From these attributes a set of audit questions was formulated and this became the evaluation manual in this work. The classification of HF spectrum was done in consultation with the industry. The main contributors were the petro-chemical and offshore industries because they have a relatively mature HF culture.

PIHFAT produces quantified results and this was achieved through analytic hierarchy process (AHP). AHP belongs to the family of multi-attribute decision analysis methods. The choice of AHP as the quantification tool was because of two reasons. First, this method has been used for many years as a decision analysis tool in various fields and has achieved sound results. It has been a very powerful tool to solve problems involving subjective reasoning. Its ability to measure consistency in subjective reasoning makes it desirable to solve HF problems where many factors and attributes are involved. Secondly, it is simple to apply and therefore was appropriate for a task that involves the industry. The author has the experience that many industries shun away from techniques as they get more complex.

PIHFAT was validated in the industry and it posted very impressive results. The time of actual validation exercise, discussions and documenting the results was five working days which was found to be justifiable. This was a remarkable observation because it was initially thought that the number of questions were not manageable. This tool is now available and could be used by both internal auditors and the authorities to assess the HF maturity levels in a given plant. Nevertheless, some suggestions were made to improve this tool. It was felt firstly, that the classification should be made broader to include the wider process industry and secondly, that more validations should be carried out.

In the second part HF were introduced into quantitative risk analysis using a newly developed procedure. It has also been argued in this work that introducing these factors will increase the accuracy of human error probabilities. In this case it means making HEPs better or worse, depending on the audit results. Here the accident modelling technique that has been chosen is fault tree. The unwanted event is deductively broken down into basic events and the ones that contain human error events are determined. After these events have been identified the underlying causes are investigated. A procedure to identify and analyse underlying HF causes was developed. It was clear that the underlying factors have different weightings and with the help of AHP a weighting system for these factors was developed. Combination of the weightings and the audit result for each factor was used to calculate the human factors modification index, which in turn is used to modify the HEPs. The effectiveness of this approach was demonstrated by use of a case study. It was shown that in one case the frequency of top event was underestimated by a factor close to 3.

It is worth mentioning that the weighting system used here was obtained from results of a survey held throughout European chemical process industry. The use of representatives from the industry brought practical sense in this work.

This work has achieved three aims. Firstly, a technique to assess human factors which has been presented in computer-based format has been developed. Secondly, a newly developed procedure to systematically analyse underlying human factors in each human error event has been illustrated. Finally the work has laid the basis for reducing the uncertainty in HEPs. The HEP data from standard methods, especially THERP and expert judgement are the ones used in almost all HRA. The introduction of the HF modification index, which was defined in this work, brings in a structured and systematic way of adjusting the HEP to reflect the actual conditions of a facility or system.

This work achieved the desired results. Nevertheless, the following are recommended for future studies:

a. Refinement of AHP hierarchy

The author feels that a further refinement is needed to group HF. The classification obtained in this work is mainly from the petro-chemical industry. The area that needs more investigation is the degree of automation because this will definitely affect the human system interface. And in turn it will affect the degree of training. A further recommendation here is to explore the applicability of fuzzy logic as an optimisation tool.

b. Classification of tasks

While carrying out the survey, some respondents felt that it is more practical to classify tasks e.g. tests and calibration, inspection, maintenance and repair, operation and emergency tasks. From here it is possible to identify the factors that influence each group and then calculate the weightings using AHP. It was felt that the factors that affect one group of tasks do not necessarily have the same weight on another group of tasks.

c. Further Validation

Although this method has proved acceptable there is a need to validate it further. It is recommended that more studies be done where a complete standard QRA have already been done.

d. Use the method to modify hardware induced failures

This study has concentrated on the human induced failures. But there are failures where the technical failures are induced by human errors. It is recommended that further investigations be done so that such failure probabilities can be adjusted using these methodologies.

List of Figures

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9 REFERENCES

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APPENDIX A: Maturity Levels for Factors and Attributes

A1: Human factors policy

POOR (level 1): Neither statement of human factors policy nor importance of considering human factors is given by the organisation.

FAIR (level 2): There is a general understanding of HF, but not in documented form.

AVERAGE (level 3): HF policy exists in a written form, but more looking for legal compliance than for continual improvement and therefore is not deep rooted within the organisation.

GOOD (level 4): HF policy exists in a written form with clear targets and objectives and it is distributed to supervisors, contractors, stakeholders and other people working for or on behalf of the organisation.

EXCELLENT (level 5): In addition to level 4, HF policy is periodically reviewed and revised to reflect the changing conditions and information in order to better look for continual improvement.

A2: Organisational and Safety Culture

POOR (level 1): There is a lack of willingness and failure to recognise and/or address those issues that might result in poor safety performance. At this stage safety is not taken seriously within the company. The safety systems in place are to fulfil the legal obligations only. It is very normal to hear statements like: "of course we have accidents- this is a dangerous business!" Bad news and near misses are ignored.

FAIR (level 2): At this stage safety is taken seriously only when an accident or incident occurs. Managers feel frustrated, because they feel the workforce does not do what they are told to or supposed to. They feel they have to force compliance. Bad news is not ignored at this level, but it is kept hidden. Improvements are only made following a serious incident.

AVERAGE (level 3): At this stage the organisation feels and knows safety as a very important issue. It has safety management systems in place. The organisation is very worried about statistics and numbers. A lot of data is collected and analysed and the organisation feels comfortable about making changes according to the collected data. The main problem here is that root causes of incidents are not investigated. At this level bad news is tolerated but still unwelcome.

GOOD (level 4): The organisation does not only concentrate on what has gone bad in the past, but they also try to consider what might go wrong in the future (proactive safety management) and prevent it before it occurs by taking the adequate steps and providing the necessary resources. At this level the HSE department starts to delegate to the workforce line and counts on them and their opinion. Management is open but still too much obsessed with statistics. Communication between management and the workforce is very good and it is well known where problems are, what is exactly happening in the organisation and the workforce knows what is expected of them. That is why the need for audits, supervision and bureaucracy decreases in this stage due to an increase in the maturity and sense for responsibility of the workforce and the organisation.

EXCELLENT (level 5): At this level the organisation seeks for continuous improvement. They set very high standards and try to reach them: compliance with the minimum regulations requirements is not enough for them. Management really knows what is happening in the organisation and they are willing to hear what goes wrong, not to blame the workforce but to improve. The workforce trusts and reports to the management what goes wrong, because they do not fear blame and they know it will be used for improvement. At this stage safety is integral to everything that is done and it is seen as a profit centre.

A3: Management of change

POOR (level 1): The company does not have a policy for change management. It neither plans the change nor assesses its risk nor does it provide the required resources. Change and its outcome are not followed up. Employees affected by change are rarely informed about the change.

FAIR (level 2): There is a general understanding of change management, but there are no change management procedures in written form. The timing of the change is not systematically planned. Concerned employees have some general information about the change.

AVERAGE (level 3): There are change management procedures in written form. Change timing and required resources are sufficiently planned after identifying people and tasks affected by change. Risks of change are roughly assessed, but workload calculations and scenario assessment are not done. Concerned employees are adequately informed about the change.

GOOD (level 4): Change management policy and procedures exist in written form with clear targets, objectives and steps. Change is well planned as long as timing and resources are concerned. Risks of change are adequately assessed, including workload calculations and scenario assessment. Participation and expertise of employees are welcome while planning and implementing the change. Employees are well informed about the change.

EXCELLENT (level 5): In addition to level 4, change management policy and procedure are periodically reviewed and revised depending on the results of the implemented changes in order to look for continual improvement of the management of change.

A4: Organisational learning (audit and reviews)

POOR (level 1): The company does not have a policy for organisational learning.

FAIR (level 2): There is a general understanding of organisational learning, but audits and reviews exist only to comply with legal and other subscribed requirements.

AVERAGE (level 3): Organisational learning policy exists in a written form with clear targets and objectives but there is no evidence of the objectivity and independence of the auditors.

GOOD (level 4): Organisational learning policy exists in a written form with clear targets and objectives with evidence of the objectivity and independence of the auditors. Audits results are important for the management reviews. Enough information and documentation are available for management at the review period.

EXCELLENT (level 5): In addition to level 4, organisational learning policy and procedures are periodically reviewed and revised in order to look for continual improvement. Reviews are very complete and they include all decisions and actions leading to changes in policy, targets, objectives or management system.

A5: Line management and supervision

POOR (level 1): The company does not have a specific plan or policy for supervision or providing with sufficient amount of equipment, protections, material, procedures, and personnel.

FAIR (level 2): There is a general understanding of supervision and line management, but there are not any clear definitions of either line management or supervisory roles and responsibilities.

AVERAGE (level 3): There is a clear definition of line management and supervisory roles and responsibilities, but still resources are not always available or sufficient when required. The suitability of people for supervisory roles is not checked and they do not receive a specific training on the matter.

GOOD (level 4): There is a clear definition of line management and supervisory roles and responsibilities. Resources are available and accessible when required. Suitability of people for supervisory roles is checked and they are specifically trained for it. Responsible for line management and supervision roles are provided with enough time, support and understanding for developing their tasks. Supervision and line management is important for the company in order to warrant safety. Supervision arrangements for contractors are partially defined.

EXCELLENT (level 5): In addition to level 4, supervision and line management are frequently evaluated and formally reported in order to improve the way supervision is delivered. Supervision arrangements for contractors are defined and supervisory problems with contractors are identified, evaluated and solved.

A6: Training

POOR (level 1): The company does not have a training program. Neither supervisors nor employees receive training specific to their work.

FAIR (level 2): There is a general training understanding in the company, but a written training program as such does not exist. Workers and supervisors receive some training but on very general terms.

AVERAGE (level 3): There is a written training program, but it is not outlined how the training is to be designed, developed or evaluated. Employees and supervisors receive adequate training assisted with a written hand out. Special times for training are set.

GOOD (level 4): There is a training program in a written form with clear targets and objectives. It outlines how to assess the trainees' needs and training requirements, as well as how to design, develop and evaluate training. The workforce involved in specialised operations also receives periodical training to review correct procedures.

EXCELLENT (level 5): In addition to level 4, the training program is periodically reviewed and revised in order to be improved. There is also a periodical assessment of training needs in order to better plan and implement refreshing training.

A7: Procedures and procedure development

POOR (level 1): Procedures and procedure management do not exist in this company.

FAIR (level 2): There is a general understanding of procedures, but procedures only exist to comply with regulation and other obligatory requirements. Procedures exist but no much attention is given to their quality or location. Procedures are ambiguous and confusing.

AVERAGE (level 3): The company understands procedures as a way of better and safer operation, but it still has not matured to a procedure management system as such. There is an interest and effort to have procedures cast in a usable form and easy to locate, but this has not materialised in a procedure management system yet.

GOOD (level 4): The company has a procedure management system, because it wants to have procedures cast in a usable form and easy to locate at the workplace. Procedures are easy to understand, written in the right language with short and simple commands ordered in the logical steps to complete a task successfully. Procedures are updated and have been revised to reflect the current state of the plant. The issue of ambiguity have been addressed.

EXCELLENT (level 5): In addition to level 4, review, evaluation and maintenance of procedures is done on a regular basis, including an exhaustive analysis of why procedures have not been followed and what can be done to improve them.

A8: Communication

POOR (level 1): Organisational communication in the company is bad. Management is unaware of what occurs in the plant and communication between teams and shifts is inexistent. As far as technical communication is concerned, the communication equipment is not very reliable and messages are often distorted or lost in or during retrieval due to the channel or technical aspects.

FAIR (level 2): There is a general understanding of organisational communication. People in the team have a general idea to whom they should address, but they are sometimes unable to deliver or receive messages on time. Management has a general idea of what happens in the plant and there is some communication between shifts and teams, but still not at an adequate level. Communication equipment reliability has been improved and messages are not distorted or lost due to channel or technical problems.

AVERAGE (level 3): The company has developed a communication system in which team components know who is to be addressed in each occasion. Information is generally available on time, but now the problem is that too much information is given and it takes time to discern the important from the irrelevant. Management wants to know what happens in the plant, but it still is not aware of the best moment or means to approach workers to acquire this information. Communication between shifts and teams is given required importance, but still the means to develop it in an adequate way have not been provided yet.

GOOD (level 4): Communication is a very important issue in the company. There is an effort to transmit only relevant information and team members know exactly to whom they must address and for whom they must receive information. Management knows what happens in the plant and has an understanding of when and how best to approach workers for information. Workers' opinion is longed for, but it is still hard for workers to express their problems to their seniors. Communication between shifts and teams is well structured and it occurs in a way of verbal or written reports. Technical communication equipment is very reliable.

EXCELLENT (level 5): In addition to level 4, communication structure is regularly revised in order to look for optimising potential. Communication within the team, between teams and shifts and with management is very fluid and the amount and relevance of information is at the optimal level.

A9: Labels and signs

POOR (level 1): Labels and signs in the company are not given much importance.

FAIR (level 2): There is a general understanding of the importance of signs and labels, but more in the sense that they only exist to comply with regulation and other obligatory requirements.

AVERAGE (level 3): The company understands signs and labels as a way for improving operations and safety, but it still has no labels and signs management system. There is an interest and effort to have signs and labels with an adequate content, placement and layout, but there is still no adequate knowledge about the best practice in design of labels and signs. It has not yet developed a standard of good sign or label.

GOOD (level 4): The company has a label and signs management system, because it wants to have signs and labels with an adequate content, placement and layout. Sign and labels are updated and have been revised, so that they are adequately placed. The company knows what makes a good label and sign and checks that every label and sign fulfil the requirements. Message and symbols are clear, obvious, short, one-meaning and easily and universally understood. Layout is adequate that the text is big and wide enough and it can be viewed horizontally, with an adequate contrast in easy to read style and colours. Labels and signs are resistant to the environmental conditions.

EXCELLENT (level 5): In addition to level 4, review, evaluation and maintenance of signs and labels is done on a regular basis, including an exhaustive analysis of why signs and labels have not fulfilled their purpose and what can be done to improve them.

A10: Documentation

POOR (level 1): The company does not have any documentation system.

FAIR (level 2): There is a general understanding of documentation, but more in the sense that it is done only to comply with regulatory requirements. Documentation is neither easy to trace nor complete.

AVERAGE (level 3): The company understands documentation as a way of improving and not just achieving compliance with requirements. Documentation management system is still undeveloped and it is sometimes difficult to trace important documents. Some documents might still be incomplete in some areas.

GOOD (level 4): The company has a good working documentation management system. Documentation is well archived and easy to find. It is up to date and it is easy to see the documents' version. It is also easy to find how often they are approved, reviewed and revised. Documentation is complete and covers all required areas.

EXCELLENT (level 5): In addition to level 4, review, evaluation and maintenance of documentation and documentation management is done on a regular basis, including an analysis of the relevance of the documentation being stored in order to find potential for improvement.

A11: Staffing

POOR (level 1): Process demands on personnel number and qualification have not been analysed and therefore it is not possible to know if there is a mismatch or not.

FAIR (level 2): Process demands on personnel number and qualification have partially been determined, but these demands are not sufficiently tackled.

AVERAGE (level 3): Process demands on personnel number and qualification have been determined and they are normally eliminated, but this is not done systematically. Personnel shortage is experienced at some instances and changes in the workload are a problem for the company.

GOOD (level 4): Process demands on personnel number and qualification are analysed and resolved in a systematic way. Task requirements are matched with the individual skills of the employees. But occasionally the company experiences a mismatch between the task demands and the number of personnel.

EXCELLENT (level 5): Process demands on personnel number and qualification have been very well determined. Task requirements are matched with the individual skills of the employees. These task demands are addressed at all times.

A12: Work schedules, shifts and overtime

POOR (level 1): Shifts are too long and work and breaks are not well scheduled. Overtime is normal practice in the company. There are not any dining rooms or food facilities.

FAIR (level 2): There is a general understanding of work schedules and shifts, but workers do not participate in the selection of the shifts. Overtime is a common practice in the company. Breaks exist, but they are not long enough.

AVERAGE (level 3): The company understands that a good work schedule and shift planning is a way for better operation and decreasing the accident rate, but a system for evaluating the effects of the shifts and work schedules on the workforce has not been developed yet. Workers can participate in the selection of shifts. There are dining rooms or warm food facilities.

GOOD (level 4): The company understands that a good work schedule and shift planning is a way for better operation and decreasing the accident rate. A system has been developed for evaluating the effects of the shifts and work schedules on the workforce. Medical surveillance and incident reports are very much considered when planning shifts and work schedules. There are dining rooms or warm food facilities.

EXCELLENT (level 5): In addition to level 4, revision and evaluation of work schedules, shifts and breaks are done periodically to check if everything is going as planned and if not implement the necessary corrective measures.

A13: Manual handling

POOR (level 1): Manual handling is common practice and very intense within the company. Moreover loads are very heavy and difficult to handle and they include either prolonged or repetitive movements, such as reaching behind the body, kneeling, squatting, reaching with hands above the shoulders or with the hands above the elbow or finger-pinch gripping or hand grasping, rotation of the forearm, and twisting the body or some other kind of movement that forces an awkward body position. Worker manual handling technique is very health damaging and workers are unaware of the risk it carries.

FAIR (level 2): Manual handling is partially substituted by automation or mechanised, not because of its potential accident risk, but because the efficiency or economics of the process is improved. It still includes many prolonged or repetitive manual handling or hand intensive tasks. Manual handling technique is still health damaging and workers are not aware of the risk it carries.

AVERAGE (level 3): There is a general understanding of the risk that bad manual handling techniques carry and therefore high risk manual handling tasks have been mechanised or automated. There are some manual handling standards that the company would like to follow, but its implementation in the company has not occurred yet.

GOOD (level 4): The company is aware of the risk involved in manual handling and there is a serious effort to substitute high risk manual handling tasks by mechanisation or automation. The risk of all manual handling activities and actions that include force, repetitive motion and performance in awkward positions has been evaluated. High risk actions have been limited. The company has accepted some good practice manual handling standards, which are implemented in the company and followed by the workers, because everyone is aware of the risk a bad manual handling carries.

EXCELLENT (level 5): In addition to level 4, a revision and evaluation of the manual handling task and its risk is done periodically to check if everything is going as planned and if not implement corrective measures.

A14: Design of controls

POOR (level 1): The design of controls is in general very poor. There is no consistency of controls with the same function across the plant and operator expectations are not fulfilled. Controls' dimensions are not adequate and inadvertent activating of controls is common.

FAIR (level 2): The design of controls is at an acceptable level in the sense that it allows operators send signals to the plant accurately and quick enough. Inadvertent activation of controls could occur in some cases, but is quickly detected. Within the plant there are controls with same function that are not designed in a consistent way. Controls still do not have the adequate dimensions and they do not completely fulfil operators' expectations.

AVERAGE (level 3): The design of controls is at an acceptable level, because it allows transmission of accurate signals on time. Inadvertent activation of controls hardly occurs. The controls with the same function are consistent across the plant. However, operators' expectations on how to operate controls are not always fulfilled.

GOOD (level 4): The design of controls could be termed as very good, because it allows transmission of accurate signals on time. The surface available for controls' installation is big enough and the controls' dimensions are adequate. Inadvertent activation of controls does not occur any more. The controls with the same function are consistent across the plant. Operators' expectations on how to operate controls are always fulfilled.

EXCELLENT (level 5): In addition to level 4, controls are periodically revised to check that their design is still at an optimal level and if not implement the necessary corrective measures.

A15: Displays

POOR (level 1): Visual displays are in general badly designed because they do not show all required information about process variables or they contain too much information. They cannot be seen from the normal working position due to either a bad location or design of the visual display. The alarm system is characterised by too many false alarms.

FAIR (level 2): Visual displays show all required information about process variables and parameters, but the display position does not completely match the schema of the process. Visual displays can be seen from the normal working position, but the information on the display cannot be adequately read due to a bad design of the visual display, such as a too small display or a bad selection of colours and other display characteristics. There is a working alarm system, but there is still clear no separation between the different levels of alarms i.e. normal, caution and critical.

AVERAGE (level 3): Quality of visual displays is at an acceptable level, because they show all required information about process variables and parameters. The display position generally matches the schema of the process. Visual displays can be seen from the normal working position, and the information on the display can be adequately read, although the design of the visual display could be improved in order to make easier reading information (bigger displays or a better selection of colours, brightness, contrast, and information presentation by symbols or text). There is an alarm management system, but the level of nuisance alarms is still high.

GOOD (level 4): Visual displays are at a very good level, because they show all required information about process variables and parameters and the display position matches the mental schema of the process. Visual displays can be seen very well from the normal working position, and a very good design of the visual display allows reading the information on the displays very well. The alarm system can be rated as very good, because the company has an alarm management system, which tries to optimise the frequency, amount and volume level of alarms in order to reduce operator overload, especially in emergency situations.

EXCELLENT (level 5): In addition to level 4, visual and auditory displays are periodically revised to check if they are still at an optimal level and if not implement the required corrective measures.

A16: Control Panels

POOR (level 1): The location of controls and displays across the plan and within the field of control panel is incoherent and inconsistent according to the rational sequence of use of controls in time and in function. Panels and their components are poorly labelled. Most frequently used components are difficult to reach. Emergency controls are difficult to identify and access.

FAIR (level 2): The design of field control panels is acceptable but the location of controls and displays across the plant does not completely match the rational sequence of use of controls in time and in function. Panels and their components are labelled, but it is still not obvious to realise how the process responds when a control is manipulated. Most frequently used controls are in general easy to reach.

AVERAGE (level 3): Location of controls and displays across the plant matches in general the rational sequence of use of controls in time and in function. Panels and their components are adequately labelled, and it is only in rare exceptions that it is not obvious to realise how the process responds when a control is manipulated. Most frequently used controls are easy to identify, but in some cases it is difficult to reach them. Emergency controls are easy to identify, but in some cases it is difficult to access them.

GOOD (level 4): Design of field control panels is very good because the location of controls and displays across the plant matches the rational sequence of use of controls in time and in function. Panels and their components are well labelled, and it is always possible to monitor process response when a control is manipulated. Most frequently used controls are easy to see and reach. Emergency controls are easy to identify and access.

EXCELLENT (level 5): In addition to level 4, fields of control panels are periodically revised to check that they are still at an optimal level, despite possible changes in the process, equipment and panels.

A17: Tools

POOR (level 1 Tool availability is very poor and it is difficult to find the needed tools. It is common to see operators using elements not specifically designed for the purpose as tools. Tool housekeeping is poor and it is common to see unused tools lying on the floors. There is no systematic program for tool maintenance.

FAIR (level 2): Tool availability is acceptable, but in some occasions it is still possible to see operators using elements not specifically designed for the purpose as tools. Tools are mainly properly stored, but difficult to find and access in some cases. Tool maintenance is partial and still inadequate and ineffective.

AVERAGE (level 3): Tool availability is very good, in the sense that the required tools are in the company, but sometimes the amount of tools is not enough and only in exceptional cases operators can be seen using elements not specifically designed for the purpose of tools. They are properly stored, and it is only in exceptional cases that tools are hard to find and access. Tool maintenance is good, although there is no specific maintenance program.

GOOD (level 4): Tool availability is very good, in the sense that the required tools are in the company, and it is not possible to see operators using elements not specifically designed for the purpose of tools. Tools are properly stored and easy to find and access. Tool maintenance is good and there is a specific maintenance program.

EXCELLENT (level 5): In addition to level 4, a revision and evaluation of tools in the plant is done periodically to check that they are still at an optimal level, despite possible changes in the process, equipment and plant activities.

A18: Equipment and valves

POOR (level 1): Design and layout of equipment and valves in the company is generally inadequate because they are not accessible when wearing working clothes and tools. Equipment and valves are poorly labelled and it is very difficult to know what happens when a local equipment control is activated or a valve is actuated. Valves are located in places hard to reach and to operate. The layout of the piping is very confusing, because there are many unnecessary crossings. There are not any or very few protections that prevent people from walking on the piping. There is no systematic program of maintaining equipment and valves.

FAIR (level 2): Most frequently used equipment can be easily accessed when wearing working clothes and tools. Equipment and valves are labelled, but it is still not obvious to realise what happens when a local equipment control is activated or a valve is opened or closed. Valve location is acceptable according to the force and position to operate it, but it is still possible to find valves located badly. The layout of the piping is sometimes confusing, because there are some unnecessary crossings. There are some protections that prevent people from walking on the piping. Equipment maintenance is partial, but still inadequate and ineffective.

AVERAGE (level 3): All equipment is generally accessible in working clothes and wearing the required tools. Equipment and valves are adequately labelled, and it is still only in rare exceptions that it is not obvious to realise what happens when a local equipment control is activated or a valve is opened or closed. Valve location is acceptable according to the force and position to operate it, and badly located valves are very rare. The layout of the piping is acceptable and the number of unnecessary crossings is minimal. The protections that prevent people from walking on the piping are acceptable. Equipment maintenance is good, although there is not a specific maintenance program.

GOOD (level 4): Equipment and valves are adequately labelled, and it is always obvious to realise what happens when a local equipment control is activated or a valve is opened or closed. Valve location is very good according to the force and position to operate it. The layout of the piping is acceptable and the number of unnecessary crossings is minimal. The protections that prevent people from walking on the piping are excellent. Equipment is good and there is a specific maintenance program.

EXCELLENT (level 5): In addition to level 4, a revision and evaluation of equipment and valves in the plant is done periodically to check if they are still at an optimal level, despite possible changes in the process, equipment and plant activities.

A19: Illumination

POOR (level 1): Light quantity is definitely inadequate at workplace. Light quality is very low because there are many observable points of glare and flicker in many parts of the room or points of the day in the workplace. There are no possibilities of adjusting artificial light sources to the personnel or the task requirements.

FAIR (level 2): Light quantity and quality are at an acceptable level in the sense that light is normally sufficient to adequately perform the task, but it is annoying and discomforting due to occasional glare and flickering. There are few possibilities of adjusting the light sources to the personnel or task requirements, but definitely not enough.

AVERAGE (level 3): Light quantity and quality are at an acceptable level because light is adequate for performing the task and it is only in rare occasions that it causes annoyance, discomfort or exhaustion. Cases of glare are very rare and light sources can be adjusted to the personnel and task requirements.

GOOD (level 4): Light quantity and quality are at a very good level, because light is very adequate for performing the task. Operators feel comfortable to work under these light conditions. Light sources can be adjusted very well to the personnel and task requirements.

EXCELLENT (level 5): In addition to level 4, light conditions are periodically revised to check that they still are at an optimal level, despite changes in the process, plant and activities.

A20: Temperature, humidity and wind chill

POOR (level 1): Temperatures at workplace are clearly too high or too low that they cause discomfort and annoyance. Protective clothes are unsuitable for the temperature levels at the workplace. It is very often, that workers have to stop working because of temperature levels, either cold or heat stress. Workers strongly complain about inadequate temperature conditions. There are no possibilities of adjusting temperature to the personnel or task requirements.

FAIR (level 2): Temperatures levels are still annoying and discomforting however tasks can be performed but only with many breaks. Workers sometimes have to stop working because of inadequate temperature levels, either cold or heat stress. There are few possibilities of adjusting temperature to the personnel or the task requirements, but definitely not enough.

AVERAGE (level 3): Temperature is at an acceptable level in the sense that it is adequate for performing the task, and it is only in rare occasions that it causes annoyance, discomfort or exhaustion. Protective clothing is designed considering the temperature level in the workplace. Workers rarely have to stop working because of inadequate temperature levels, either cold or heat stress, but they still sometimes complain about inadequate temperature conditions. When possible, temperatures can be adjusted to the personnel and task requirements.

GOOD (level 4): Temperatures are maintained at very good level and therefore provide good conditions for performing the task. Operators feel comfortable to work under these temperature conditions. Temperature can be adjusted very well to the personnel and task requirements.

EXCELLENT (level 5): In addition to level 4, temperature conditions are periodically revised to check that they still are at an optimal level, despite changes in the process, plant and activities.

A21: Noise

POOR (level 1): Noise level is definitely inadequate at the workplace and it causes discomfort and annoyance and therefore can easily induce errors while performing the task. Noise levels exceed the permissible exposure from OSHA standards. Workplace is not adapted for noise and workers do not wear protection devices.

FAIR (level 2): Noise is at an acceptable level in the sense that it is at upper limit of the OSHA standards or other regulatory requirements for permissible exposure. The workplace is partially adapted to noise and workers wear protection devices only on rare occasions.

AVERAGE (level 3): Noise is at an acceptable level in the sense that it is within the OSHA standards or other requirements, and it is only in few sections that it causes annoyance and discomfort. The workplace is in general well adapted to noise and workers wear the required protection devices.

GOOD (level 4): Noise is at a very good level and can hardly affect task performance. Workplace is very well adapted to noise and workers wear the required protections.

EXCELLENT (level 5): In addition to level 4, noise conditions are periodically revised to check that they still are at an optimal level, despite changes in the process, plant and activities.

A22: Vibration

POOR (level 1): Vibration level is very high and it causes discomfort and annoyance while performing the task. Vibration levels exceed the permissible exposure levels for health. Workplace is not adapted to vibration. Neither the company nor the workers are aware of the negative effects of vibration on health or as a cause of errors during task performance.

FAIR (level 2): Vibration is at an acceptable level in the sense that it is at the limit of the permissible exposure levels, but it is annoying and discomforting. Operators could be induced to making errors due to high vibration level. Workplace is partially adapted for vibration, but there is only a vague understanding of the negative effects of vibration on health or as a cause of errors during task performance.

AVERAGE (level 3): Vibration is at an acceptable level in the sense that it is within permissible exposure levels, and it is only in rare occasions that it causes annoyance and discomfort. Workplace is in general well adapted to vibration and there is a good understanding of the negative effects of vibration on health or as a cause of errors during task performance.

GOOD (level 4): Vibration levels are very low, and therefore chances for inducing errors during task performance or damaging health are low. Workplace is very well adapted for vibration and there is a high awareness of the negative effects of vibration on health or as a cause of errors during task performance .

EXCELLENT (level 5): In addition to level 4, vibration conditions are periodically revised to check that they still are at an optimal level, despite changes in the process, plant and activities.

A23: Toxicity and air quality

POOR (level 1): Air quality is evidently very bad. It ma sometimes happen, that workers have to stop working because of the bad air quality levels and they strongly complain about air quality conditions. Workplace has not got devices to improve the air quality.

FAIR (level 2): Air quality is at an acceptable level in the sense, but it still causes slight discomfort. Workers rarely have to stop working because of bad air quality levels, but they complain about inadequate air quality conditions. Workplace has got ventilation system, but it is definitely not good enough.

AVERAGE (level 3): Air quality is at an acceptable level and only in rare occasions does it causes discomfort. Workers do not have to stop working because of inadequate air quality levels, but they still sometimes complain about the air quality conditions. Ventilation is in general good at the workplace.

GOOD (level 4): Air quality is at a very good level and operators feel comfortable to work under these air quality conditions. Ventilation is very good.

EXCELLENT (level 5): In addition to level 4, air quality conditions are periodically revised to check that they still are at an optimal level, despite changes in the process, plant and activities.

A24: Facility layout

POOR (level 1): Facility layout is in general very poor. The design or construction has not taken into consideration the risk during operations, inspection, testing, maintenance, modification, repair and replacement. High risk equipment and processes are located close to storage areas. The escape routes are narrow and insufficient in case of an emergency situation.

FAIR (level 2): The process design has taken into consideration risks associated with the operations. The layout has followed minimum safety design standards but fails to optimise using tools like link analysis. There is some evidence that risky processes have been clearly separated.

AVERAGE (level 3): It is evident that the facility layout has considered the risk during operations, inspection, testing, maintenance, modification, repair and replacement during the design stage. Safety design standards guidelines have been followed. In some cases a systematic methods like link analysis have been used.

GOOD (level 4): It is fully evident that apart from regulatory obligations there has been application of link and task analysis to optimise on safety and operability. Hazardous equipment and process are located in separate areas. The escape routes are sufficient in case of emergency situations

EXCELLENT (level 5): In addition to level 4, facility layout is periodically revised to check that it is still at an optimal level, and if not study the implementation of changes or secondary measures to improve the situation.

A25: Workstation configuration

POOR (level 1): Workstations are evidently not configured to suit operators' characteristics. They are definitely not big enough to allow free movement during task performance.

FAIR (level 2): Workstations are configured to some extent according to the PRISM guidelines, but do not take into consideration the majority of workers. Operators can easily manoeuvre around when performing their normal tasks but would experience some difficulties during emergency conditions.

AVERAGE (level 3): There is evidence that the workstations are configured to follow PRISM guidelines and other standards for workstation configuration but this has not been yet standardised as the across the plant. There is an effort to improve the current general conditions.

GOOD (level 4): Workstations are configured to follow PRISM guidelines and other standards for workstation configuration. It is evidently visible that the whole plant has been standardised and the areas that may need improvement are identified.

EXCELLENT (level 5): In addition to level 4, workstation configuration is periodically revised to check that it still is at an optimal level, and if not study the implementation of changes or secondary measures to improve the situation.

A26: Accessibility

POOR (level 1): It is very often that people have difficulties to reach required equipment, visual displays and controls and parts of the plant during operations, inspections, and maintenance and or repair operations. Cranes or people wearing clothing and tools required to work have difficulties to access some of the required parts of the plant. Pathways are not free of obstructions or hanging objects or/and they do not allow the shortest way without needing to disconnect or move other machinery. Emergency pathways are not clearly marked.

FAIR (level 2): People are able to access many of the required work interfaces even with personal protective equipment but with some difficulties. Pathways are mainly free of obstructions or hanging objects, but they do not always allow the shortest way without having to disconnect or move other machinery. Emergency pathways are mainly clearly marked.

AVERAGE (level 3): There is evidence that people can easily reach required equipment, visual displays and controls and parts of the plant during operations, inspections, maintenance and or repair operations. Cranes or people wearing PPE can access the required parts of the plant without difficulties. Pathways are free of obstructions or hanging objects, but they almost always allow the shortest way without needing to disconnect or move other machinery. Emergency pathways are clearly marked.

GOOD (level 4): Accessibility design has fulfilled the best practice because all the work interfaces can easily be accessed even during emergency situations. Cranes or people wearing PPE can access the required parts of the plant without difficulties. Pathways are free of obstructions or hanging objects and they allow the shortest way without needing to disconnect or move other machinery. Emergency pathways are clearly marked.

EXCELLENT (level 5): In addition to level 4, accessibility is periodically revised to check that it is still at an optimal level, despite possible changes in the process and facility layout, and if not study the implementation of changes or secondary measures to improve the situation.

A27: Control room design

POOR (level 1): Control room is located in a hazardous place within the plant. Equipment in the control room has not been arranged considering the operators' functions and their interactions with equipment. Visibility is partially hindered by consoles or equipment. It is frequent to see non-essential personnel in the main working areas. Illumination is not adjustable and glare occurs at some parts of the day or in some parts of the room. The communication system is hard to access from the primary working areas. Noise level is discomforting and annoying and it negatively affects the work performance in the control room as well as the communication with outside the control room.

FAIR (level 2): Control room is located in a less hazardous place. Equipment in the control room has been partially arranged considering the operators' functions and their interactions with equipment but this has not been done systematically. Non-essential personnel are sometimes seen in the main working areas. At seated position the operator is facing the visual display board. The communication system is easy to access from the primary working areas. Noise level is within the standards, but it is still discomforting and annoying and it sometimes affects communication with outside the control room.

AVERAGE (level 3): Control room is located in a less hazardous place. Equipment in the control room has been arranged considering the operators' functions and their interactions with equipment. Visibility is rarely hindered. Non-essential personnel are rarely seen in the main working areas. At seated position the operator is facing the visual display board. Illumination is adjustable and glare occurs very rarely. The communication system is easy to access from the primary working areas. Control room is fairly quite.

GOOD (level 4): Control room is located at a very safe place where it would rarely be affected in case of an accident. Equipment in the control room has been arranged considering the operators' functions and their interactions with equipment and this has been done by use of link analysis. The good design of the control room allows simultaneous access for operator and maintenance team. When seated the operator is facing the visual display board. Illumination is indirect, adjustable and glare does not occur. The communication system is easy to access from the primary working areas. Noise level and air quality are very good. Reference materials are easy to find and use in the control room, and employees are also encouraged to use them.

EXCELLENT (level 5): In addition to level 4, revision and evaluation of control room are done periodically to check if the control room is still at an optimal level, despite possible changes in the process, equipment and plant activities, and if not study the implementation of changes or secondary measures to improve the situation.

A28: Skills and knowledge

POOR (level 1): It is evident that task requirements are deeply mismatched with the operators' skills. Operators' skills and knowledge are not sufficient to allow correct task performance. Operators do not possess the required qualifications to perform the task that has been assigned to them.

FAIR (level 2): Some training has been done to improve operator's skills and knowledge, but there is still a mismatch between the task requirements and the employees' abilities. An improvement in operators' skills and knowledge would allow a better task performance.

AVERAGE (level 3): Apart from training there is an effort to assign only experienced operators to complex tasks. Operator's skills and knowledge are analysed before assigning a specific task.

GOOD (level 4): It is within the company's policies that operators' skills are matched to the task. Experience is considered very important and training is used as a means to improve this.

EXCELLENT (level 5): In addition to level 4, skills and knowledge are periodically revised to check that they are still at an optimal level, and if not study the implementation of changes or secondary measures to improve the situation.

A29: Attention/Motivation

POOR (level 1): Operators cannot concentrate well on conflicting messages. Employees are unable to attend an incoming input because they are attending to other inputs. Workers do not feel their work as being important and they also have the impression that it is not recognised by supervisors, colleagues and/or subordinates. Self reporting is avoided because of the blame culture.

FAIR (level 2): There is still an overload due to information provided to the workers. They sometimes have problems to deal with an incoming input because they are already attending to some other input. Employee satisfaction at and with work can be improved.

AVERAGE (level 3): It is only in exceptional cases that operators are overloaded. Employees feel their work is recognised by supervisors, colleagues and/or subordinates. Employee satisfaction at and with work is acceptable.

GOOD (level 4): The amount of information provided to the workers is optimal such that it does not provide overload. Employee satisfaction with and at work is very high. The workers are highly motivated and are able to report any obstacles that affect performance because it is encouraged.

EXCELLENT (level 5): In addition to level 4, factors that affect attention and motivation are periodically revised to check that they still are at an optimal level despite changes in the process, equipment and operators' conditions and if not study the implementation of changes or secondary measures to improve the situation.

A30: Fitness for duty

Fitness for duty is the ability to perform activities within an occupation or function to the standards expected in employment (Wright et al., 2002). This refers to matching individuals to tasks to ensure an adequate outcome. Individuals should be able to successfully undertake the specific tasks and activities to which they are assigned.

POOR (level 1): There is evidence that workers are often fatigued due to long continuous working hours without breaks or experience inadequate rest due to long and unplanned shifts. Operator could be impaired due to poor health condition or sometime there are cases where operator is under influence of alcohol or drugs prior to or during working hours.

FAIR (level 2): There is demonstrated effort to regulate shifts in order to reduce fatigue, make pauses and control of alcohol and drugs during working hours. Still a lot has to be done to integrate this into the company's policies.

AVERAGE (level 3): There is a systematic planning of breaks and shifts but the knowledge of optimal shifts planning is not available. There are still some cases of alcohol consumption during working hours.

GOOD (level 4): There is a complete understanding of the effects of long shifts on human performance. They are well planned, documented and have become part of the companies norms. There is a strict control of alcohol and drugs during working hours.

EXCELLENT (level 5): In addition to level 4, factors affecting fitness for duty are periodically revised to check that it is still at an optimal level, despite possible changes in the process and staff and if not study the implementation of changes or secondary measures to improve the situation.

Appendix B

Profession:

Industry:

Years of Experience:

Based on the above classification, how would you rate the following factors according to their importance on how they contribute to human error events?

Table B-1: Rating of human factors

	Least important	Important	Moderately important	Highly important	Extremely important
Organisation and management	☐	☐	☐	☐	☐
Information	☐	☐	☐	☐	☐
Job Design	☐	☐	☐	☐	☐
Human System Interface	☐	☐	☐	☐	☐
Task Environment	☐	☐	☐	☐	☐
Workplace Design	☐	☐	☐	☐	☐
Operator Characteristics	☐	☐	☐	☐	☐

And now how would you rate these attributes using the same scale?

Table B-2: Rating of human factors attributes

Attributes	Least important	Important	Moderately important	Highly important	Extremely important
Human factors and safety policy	☐	☐	☐	☐	☐
Organisational culture	☐	☐	☐	☐	☐
Management of change	☐	☐	☐	☐	☐
Organisational learning (audit & reviews)	☐	☐	☐	☐	☐
Line management & supervision	☐	☐	☐	☐	☐
Training	☐	☐	☐	☐	☐
Procedures & procedure development	☐	☐	☐	☐	☐
Communication	☐	☐	☐	☐	☐
Labels & signs	☐	☐	☐	☐	☐
Documentation	☐	☐	☐	☐	☐
Staffing	☐	☐	☐	☐	☐
Shifts & overtime	☐	☐	☐	☐	☐
Manual handling.	☐	☐	☐	☐	☐
Design of controls	☐	☐	☐	☐	☐
Displays	☐	☐	☐	☐	☐
Field control panels	☐	☐	☐	☐	☐
Tools (hand)	☐	☐	☐	☐	☐
Equipment & valves	☐	☐	☐	☐	☐
Lighting	☐	☐	☐	☐	☐
Temperatures	☐	☐	☐	☐	☐
Noise	☐	☐	☐	☐	☐
Vibration	☐	☐	☐	☐	☐
Toxicity	☐	☐	☐	☐	☐
Facility layout	☐	☐	☐	☐	☐
Workstation configuration	☐	☐	☐	☐	☐
Accessibility	☐	☐	☐	☐	☐
Attention/ motivation	☐	☐	☐	☐	☐
Fitness for duty	☐	☐	☐	☐	☐
Skills and knowledge	☐	☐	☐	☐	☐

Table B-3: Weights distribution of factors from all the judges

	Judge																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Mean	STD Deviation
Organisation and management	0.04	0.18	0.35	0.39	0.28	0.05	0.06	0.39	0.33	0.27	0.09	0.20	0.13	0.37	0.03	0.42	0.11	0.25	0.16	0.18	0.06	0.16	0.36	0.21	0.13
Information	0.08	0.18	0.14	0.19	0.10	0.05	0.14	0.19	0.11	0.09	0.27	0.04	0.13	0.16	0.05	0.23	0.29	0.11	0.16	0.06	0.18	0.16	0.14	0.14	0.07
Job Design	0.18	0.07	0.14	0.08	0.04	0.11	0.14	0.09	0.11	0.27	0.10	0.38	0.13	0.16	0.10	0.11	0.11	0.05	0.16	0.06	0.18	0.06	0.14	0.13	0.07
Human System Interface	0.18	0.07	0.05	0.08	0.10	0.29	0.15	0.18	0.11	0.09	0.10	0.04	0.13	0.07	0.24	0.05	0.29	0.25	0.06	0.06	0.06	0.16	0.14	0.13	0.07
Task Environment	0.04	0.03	0.14	0.04	0.10	0.11	0.03	0.03	0.11	0.09	0.27	0.04	0.03	0.03	0.24	0.05	0.11	0.05	0.06	0.18	0.18	0.03	0.03	0.09	0.07
Workplace Design	0.40	0.07	0.14	0.04	0.10	0.11	0.31	0.03	0.11	0.09	0.12	0.16	0.13	0.03	0.24	0.11	0.05	0.25	0.06	0.06	0.18	0.06	0.03	0.13	0.09
Operator Characteristics	0.08	0.38	0.05	0.19	0.29	0.29	0.18	0.09	0.11	0.09	0.04	0.14	0.34	0.16	0.11	0.03	0.05	0.05	0.36	0.38	0.18	0.37	0.14	0.18	0.12

Table B-4: Weights distribution of attributes from all judges

	Judge																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	Mean	STD Deviation
Human factors and safety policy	0.06	0.06	0.13	0.27	0.17	0.07	0.25	0.07	0.11	0.06	0.04	0.29	0.04	0.06	0.50	0.34	0.27	0.35	0.27	0.11	0.20	0.07	0.20	0.17	0.12
Organisational culture	0.17	0.34	0.34	0.27	0.44	0.43	0.11	0.26	0.33	0.34	0.36	0.06	0.34	0.44	0.09	0.13	0.09	0.08	0.27	0.11	0.20	0.20	0.20	0.24	0.12
Management of change	0.17	0.13	0.13	0.09	0.06	0.10	0.05	0.50	0.33	0.34	0.36	0.06	0.14	0.17	0.09	0.06	0.27	0.14	0.27	0.33	0.20	0.46	0.20	0.20	0.13
Organisational learning (audit & reviews)	0.17	0.34	0.34	0.09	0.17	0.20	0.11	0.13	0.11	0.13	0.08	0.29	0.14	0.17	0.09	0.13	0.09	0.14	0.12	0.11	0.20	0.07	0.20	0.16	0.08
Line management & supervision	0.44	0.13	0.06	0.27	0.17	0.20	0.50	0.03	0.11	0.13	0.16	0.29	0.34	0.17	0.24	0.34	0.27	0.31	0.08	0.33	0.20	0.20	0.20	0.22	0.12
Training	0.14	0.16	0.20	0.14	0.46	0.33	0.28	0.34	0.23	0.27	0.30	0.34	0.23	0.46	0.14	0.09	0.27	0.56	0.09	0.23	0.28	0.46	0.20	0.27	0.12
Procedures & procedure development	0.14	0.16	0.46	0.14	0.07	0.11	0.28	0.15	0.23	0.09	0.30	0.14	0.08	0.20	0.43	0.21	0.09	0.13	0.09	0.08	0.28	0.07	0.20	0.18	0.11
Communication	0.14	0.56	0.20	0.43	0.20	0.33	0.28	0.34	0.23	0.27	0.30	0.14	0.23	0.20	0.14	0.45	0.27	0.13	0.27	0.23	0.28	0.20	0.46	0.27	0.11
Labels & signs	0.43	0.04	0.07	0.14	0.20	0.11	0.11	0.05	0.08	0.09	0.04	0.04	0.23	0.04	0.14	0.21	0.27	0.13	0.27	0.23	0.05	0.07	0.07	0.14	0.10
Documentation	0.14	0.08	0.07	0.14	0.07	0.11	0.05	0.13	0.23	0.27	0.04	0.34	0.23	0.09	0.14	0.05	0.09	0.05	0.27	0.23	0.11	0.20	0.07	0.14	0.08
Staffing	0.43	0.43	0.33	0.20	0.20	0.33	0.33	0.43	0.71	0.20	0.28	0.20	0.63	0.78	0.33	0.20	0.26	0.63	0.43	0.45	0.20	0.26	0.45	0.38	0.17
Shifts & overtime	0.43	0.43	0.33	0.20	0.60	0.33	0.33	0.43	0.14	0.60	0.64	0.60	0.11	0.15	0.33	0.60	0.63	0.26	0.43	0.23	0.20	0.63	0.45	0.40	0.17
Manual handling.	0.14	0.14	0.33	0.60	0.20	0.33	0.33	0.14	0.14	0.20	0.07	0.20	0.26	0.07	0.33	0.20	0.11	0.11	0.14	0.32	0.60	0.11	0.09	0.23	0.14
Design of controls	0.23	0.20	0.43	0.27	0.20	0.27	0.17	0.05	0.44	0.20	0.44	0.14	0.20	0.20	0.27	0.14	0.27	0.15	0.20	0.17	0.11	0.11	0.20	0.22	0.10
Displays	0.23	0.20	0.14	0.27	0.46	0.12	0.17	0.50	0.17	0.20	0.17	0.34	0.20	0.46	0.27	0.43	0.27	0.36	0.20	0.17	0.11	0.33	0.20	0.26	0.11
Field Control Panels	0.23	0.20	0.14	0.09	0.07	0.27	0.17	0.25	0.06	0.20	0.17	0.14	0.20	0.20	0.27	0.14	0.27	0.06	0.20	0.06	0.11	0.33	0.20	0.18	0.07
Tools (hand)	0.08	0.20	0.14	0.27	0.20	0.27	0.44	0.11	0.17	0.20	0.04	0.34	0.20	0.07	0.09	0.14	0.09	0.36	0.20	0.44	0.33	0.11	0.20	0.20	0.11
Equipment & valves	0.23	0.20	0.14	0.09	0.07	0.08	0.06	0.11	0.17	0.20	0.17	0.04	0.20	0.07	0.09	0.14	0.09	0.06	0.20	0.17	0.33	0.11	0.20	0.14	0.07
Lighting	0.23	0.11	0.33	0.43	0.33	0.09	0.06	0.06	0.15	0.11	0.08	0.33	0.20	0.20	0.20	0.17	0.33	0.23	0.14	0.14	0.14	0.15	0.20	0.19	0.10
Temperatures	0.23	0.11	0.33	0.14	0.33	0.27	0.35	0.03	0.36	0.11	0.16	0.11	0.20	0.20	0.20	0.17	0.11	0.23	0.14	0.14	0.14	0.06	0.20	0.19	0.09
Noise	0.23	0.33	0.11	0.14	0.11	0.27	0.13	0.22	0.06	0.11	0.36	0.11	0.07	0.20	0.20	0.37	0.11	0.23	0.14	0.14	0.14	0.36	0.20	0.19	0.09
Vibration	0.23	0.33	0.11	0.14	0.11	0.27	0.10	0.22	0.06	0.11	0.36	0.11	0.07	0.20	0.20	0.24	0.11	0.23	0.14	0.14	0.14	0.36	0.20	0.18	0.09
Toxicity	0.08	0.11	0.11	0.14	0.11	0.09	0.35	0.47	0.36	0.56	0.04	0.33	0.46	0.20	0.20	0.06	0.33	0.08	0.43	0.43	0.43	0.06	0.20	0.25	0.16
Facility Layout	0.13	0.50	0.25	0.17	0.38	0.30	0.17	0.52	0.25	0.30	0.15	0.10	0.10	0.10	0.25	0.25	0.17	0.10	0.25	0.17	0.25	0.30	0.50	0.25	0.13
Workstation configuration	0.38	0.17	0.25	0.17	0.13	0.30	0.17	0.20	0.25	0.30	0.39	0.30	0.30	0.30	0.25	0.10	0.17	0.30	0.25	0.17	0.25	0.30	0.17	0.24	0.08
Accessibility	0.13	0.17	0.25	0.50	0.38	0.10	0.50	0.08	0.25	0.10	0.07	0.30	0.30	0.30	0.25	0.55	0.50	0.30	0.25	0.50	0.25	0.10	0.17	0.27	0.15
Control Room	0.38	0.17	0.25	0.17	0.13	0.30	0.17	0.20	0.25	0.30	0.39	0.30	0.30	0.30	0.25	0.10	0.17	0.30	0.25	0.17	0.25	0.30	0.17	0.24	0.08
Attention/ motivation	0.33	0.47	0.20	0.60	0.64	0.11	0.63	0.45	0.43	0.20	0.43	0.14	0.45	0.43	0.14	0.60	0.63	0.63	0.60	0.33	0.33	0.43	0.43	0.42	0.17
Fitness for duty	0.33	0.07	0.20	0.20	0.07	0.26	0.11	0.09	0.14	0.20	0.14	0.43	0.09	0.14	0.43	0.20	0.26	0.11	0.20	0.33	0.33	0.14	0.43	0.21	0.11
Skills and knowledge	0.33	0.47	0.60	0.20	0.28	0.63	0.26	0.45	0.43	0.60	0.43	0.43	0.45	0.43	0.43	0.20	0.11	0.26	0.20	0.33	0.33	0.43	0.14	0.37	0.14